AFWAL-TR-85-4138

(2)

AD-A165 289

EVALUATION OF THE EFFECTS OF A PLASTIC BEAD PAINT REMOVAL PROCESS ON PROPERTIES OF AIRCRAFT STRUCTURAL MATERIALS

Sidney Childers
David C. Watson
Patricia Stumpff
Jon Tirpak, 1st Lt, USAF

Materials Integrity Branch
Systems Support Division

December 1985

Final Report for Period October 1984 to August 1985.

Approved for public release; distribution unlimited.

MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AFB, OHIO 45433

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This technical report has been reviewed and is approved for publication.

Sidney Childers
SIDNEY CHILDERS, Project Engineer
Materials Integrity Branch

Thomas D Cooper
THOMAS D COOPER, Chief
Materials Integrity Branch
Materials Laboratory

David C Watson
DAVID C. WATSON, Project Engineer
Materials Engineering Branch

PATRICIA STUMPFF, Project Engineer
Materials Integrity Branch

Jon Tirpak
JON TIRPAK, 1LT, USAF, Project Engineer
Materials Integrity Branch

FOR THE COMMANDER:

W. P. JOHNSON, Chief
Systems Support Division
Materials Laboratory

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

AD-A165289

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY: N/A

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S): AFWAL-TR-85-4138

5. MONITORING ORGANIZATION REPORT NUMBER(S): N/A

6a. NAME OF PERFORMING ORGANIZATION: Materials Laboratory

6b. OFFICE SYMBOL (If applicable): MLSA

7a. NAME OF MONITORING ORGANIZATION: N/A

6c. ADDRESS (City, State and ZIP Code): Wright-Patterson AFB, OH 45433-6533

7b. ADDRESS (City, State and ZIP Code): N/A

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AF Wright Aeronautical Lab, Materials Lab

8b. OFFICE SYMBOL (If applicable): AFWAL/MLSA

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: N/A

8c. ADDRESS (City, State and ZIP Code): Wright-Patterson AFB, Oh 45433

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
62102	2418	07	04

11. TITLE (Include Security Classification): Evaluation of the Effects of a Plastic Bead Paint Removal Process on Properties of Aircraft Structural Materials

12. PERSONAL AUTHOR(S): Sidney Childers, David C. Watson, Patricia Stumpff, Jon Tirpak

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM Oct 84 TO Aug 85

14. DATE OF REPORT (Yr., Mo., Day): December 1985

15. PAGE COUNT: 151

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB. GR.
11	03	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Paint Removal, ~~Abrasive Blasting, Plastic Bead~~ Fatigue, Fatigue Life, ~~Surface Roughness, Metal, Aluminum, Composite~~ Epoxy Graphite.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

An abrasive blasting process using plastic beads has been proposed for removing organic coatings from aircraft surfaces and component parts. During the prototype development of the plastic bead blasting process for paint removal many concerns surfaced relative to the potential effects of the process on metal and composite aircraft structural materials. This evaluation of the plastic bead blasting paint removal showed that it removed protective metal coatings such as aluminum cladding and anodize coatings from aluminum alloys and cadmium plating from steel structure. Surface roughness resulted on clad aluminum alloys. Warpage as a result of surface cold working occurred on unsupported thin skin metal materials. The bond strength of thin skin adhesive bonded structure was not affected. The process is less damaging in fatigue to 7075-T6 aluminum structure blasted at 60 psi nozzle pressure than at 38 psi nozzle pressure. Epoxy/graphite composite structure which was plastic bead blasted showed statistically significant losses in the matrix dominated properties. No significant reductions occurred in the fiber dominated mechanical properties. Keywords

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Sidney Childers

22b. TELEPHONE NUMBER (Include Area Code): (513) 255-3637

22c. OFFICE SYMBOL: AFWAL/MLSA

FOREWORD

This Technical Report was prepared by Sidney Childers, David C. Watson, Patricia Stumpff and Jon Tirpak, 1 Lt/USAF of Air Force Wright Aeronautical Laboratories, Materials Laboratory, Wright-Patterson AFB, Ohio. The work for this report was performed at the Materials Laboratory during the period October 1984 to August 1985. The authors wish to thank the following individuals who contributed substantially to this report:

Mr T. D. Cooper, AFWAL/MLSA
Mr R. H. Williams, AFWAL/MLSA
1Lt Ray Belz, AFWAL/MLSE
Sgt Joel Dyksterhouse, AFWAL/MLSE

This report was submitted by the authors in August 1985.

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SECTION I

INTRODUCTION

Paint coatings are used to perform multifunctional purposes on virtually all aircraft systems and associated support equipment including protection against corrosion, camouflage, thermal protection, and erosion resistance. During the life of the weapon systems, the coatings require removal for a variety of reasons from replacement of the worn coatings to changes in camouflage schemes. Removal of the chemically resistant coatings used on weapon systems is labor intensive and require the use of strongly activated chemical strippers.

Paint removal technology has not kept pace with the rapid advances of new polymeric resins in the coatings industry. When alkyd primers and alkyd enamel topcoats and alkyd primers and acrylic nitrocellulose topcoats were used as coating materials, their removal was easily accomplished with solvent based strippers which were predominately methylene chloride. However, as coatings transitioned from alkyds and nitrocelluloses to epoxies, polyurethanes and fluoropolymers, the traditional solvent type strippers were no longer effective removers for the new polymers. Also, the alkyds and acrylic nitrocelluloses were functional for only one to two years as they eroded easily and were severely attacked by aircraft fluids, leaving very little of the coating to be removed. Presently used coatings have a life expectancy of five to seven years due to their excellent environmental, erosion and fluid resistance. The longevity of epoxy and polyurethane coatings further complicates their removal as they become progressively resistant to chemical strippers due to complete polymerization and aging from exposure to the environment, engine heat, exhaust, and aerodynamic heating.

The approach taken by the chemical industry to provide strippers for presently used coatings has been to add an "activator" to the traditional solvent type strippers. The commonly used activators are phenols and amines. These strippers do not effectively or economically remove the epoxy and polyurethane coatings. As many as five applications are required together with aggressive mechanical agitation using powered and hand brushing. The phenolic activated strippers are more efficient than the amine activated strippers, however, the phenols are not biodegradable and cause water pollution problems when used in large quantities. Also hexavalent chromium compounds are used in the strippers as corrosion inhibitors which further restricts the use of present strippers from an environmental standpoint.

Additionally, organic matrix composites, such as graphite/epoxy, are now being used as aircraft structure. These same coating materials are bei applied to these composite components that are applied to the metal skins. Chemica. paint strippers cannot be used for paint removal from composite structure because of the high risk that they will chemically attack the organic matrix material.

As an alternative process to chemical paint stripping, mechanical paint removal by abrasive blasting using various abrasive media has been investigated at length. Abrasive media that have been evaluated include crushed corn cobs, glass beads, walnut shells, synthetic diamond dust, garnet, and "dry ice" pellets. Also high pressure water has been evaluated for paint removal from aircraft surfaces. All methods have shown limited success.

A project was initiated at Ogden Air Logistics Center (ALC), Hill AFB, Utah, under a producibility, reliability, availability and maintainability (PRAM) program, to evaluate a plastic bead media for abrasively removing paint from F-4 aircraft. The plastic media is either thermosetting polyester or melamine formaldehyde plastic in random angular shapes in various seive sizes. The plastic bead media range in hardness of 3.5 to 4.0 on the Moh scale. The initial application of this plastic bead paint removal process at Hill AFB was for stripping paint from F-4 aircraft wingfolds. Since then, the plastic bead paint stripping process has been developed into a prototype facility capable of stripping an entire F-4 aircraft.

During the testing and prototype development of the plastic bead blasting process by Ogden ALC, several concerns surfaced relative to the potential effects of the process on aircraft materials. The concerns are as follows:

a. Surface roughness and its potential resulting effects on aerodynamic drag.

b. Fatigue properties of metal alloys as a result of the surface roughness.

c. Removal of protective metal coatings such as aluminum cladding and anodize coatings from aluminum alloys and cadmium plating from steel structure.

d. Effects on the bond strength of aluminum honeycomb and thin skin aluminum metal to metal bonded structure.

e. Effects on the physical properties of graphite/epoxy composite materials.

f. Intrusion and consequent effects of the plastic particulate matter on the wear properties of lubricated bearings.

g. Thin skin warpage as a result of surface cold working.

h. Effects on fatigue crack growth rate as a result of compressive residual stress on the surface and a tensile residual stress in subsurface material.

i. Effects on dye penetrant inspection techniques.

j. Intrusion of plastic particles into avionic compartments.

As a result of the above concerns, the Systems Support Division (AFWAL/MLS) was requested by HQ AFLC/MAX to initiate a test program to assess any potential damage to aircraft materials.

This report presents the results of the test program and is divided into four sections and two appendices. Section I is an overview and introduction to the program. Section II describes the test program, test materials, and test procedures. Section III presents the test results and analysis. Guidelines for evaluating the effects of plastic bead paint removal on metallic materials considered fracture critical as well as other parts are presented in Section IV of the report.

SECTION II

TEST PROGRAM AND PROCEDURES

The purpose of this test program was to obtain data on any adverse physical effects of a plastic bead blast paint removal process on "worst case" aerospace structural materials. The structural materials selected are believed to be "worst case" because they would be most likely to receive damage affecting their strength properties from the plastic bead blasting paint removal process.

A. MATERIALS TESTED

1. Thin Skin Aluminum Honeycomb Structure

(a) Face Sheets - 0.016 inch thick 7075-T6 alclad aluminum alloy.

(b) Face sheet preparation for bonding - chromic acid anodized and coated on one side with BR-127 bonding primer.

(c) Honeycomb core material - 5052 aluminum

(d) Honeycomb core thickness - 0.5 in

(e) Honeycomb core density - 2.3 lb/cu ft

(f) Bonding adhesive - Hysol epoxy 9601.2

2. Thin Skin Aluminum Metal to Metal Bonded Structure

(a) Aluminum material - 0.016 in 7075-T6 alclad aluminum alloy

(b) Bonding preparation - Chromic acid anodized and coated on one side with BR-127 bonding primer.

(c) Bonding adhesive - Hysol epoxy 9601.2

3. Unclad 7075-T6 Aluminum Alloy

(a) Thickness - 0.063 inch

(b) Treatment - Sulfuric acid anodized and dichromate sealed.

4. Graphite/Epoxy Composite Panels

(a) Material - Hercules AS4/3501-6 12 ply.

(b) Fiber Orientation

(1) 0° unidirectional
(2) 90° unidirectional
(3) $[0/\pm45/0/90/0]_s$
(4) $[90/0/\pm45/90]_s$
(5) $[\pm45/0_2/90/0]_s$

B. PANEL QUALITY ASSURANCE

1. Aluminum Test Panels

(a) All panels were ultrasonically inspected initially to ensure the absence of debonded areas or voids in the adhesively bonded structure. All panels were ultrasonically inspected after each paint removal process to ensure that no debonding had occurred as a result of the blasting process.

(b) Surface roughness (in microinches) was measured on all metal panels initially and after each paint removal.

(c) Baseline mechanical properties (fatigue and adhesive bond strength) were determined on all materials having no paint removal.

(d) All anodized aluminum test panels had electrical surface conductivity tests accomplished before and after paint removal to determine removal of the anodize coating.

(e) All metal to metal bonded aluminum panels were visually inspected for warpage resulting from surface cold working.

2. GRAPHITE/EPOXY COMPOSITE TEST PANELS

(a) All panels were initially ultrasonically inspected to ensure the absence of debonded areas or other abnormalities in the bonded structure. All panels were ultrasonically inspected after each paint removal process to ensure that no ply debonding or matrix cracking had occurred as a result of the blasting process.

(b) The panels were x-rayed before and after each paint removal process to determine any macro areas of fiber breakage or internal matrix damage.

(c) Physical property and baseline mechanical properties (tensile strength and modulus and four point flexural strength) were determined on the material having no paint removal.

(d) Sections were taken from the test panels before and after each paint removal and inspected by scanning electron microscope for fiber breakage, matrix cracking, and fiber/matrix debonding.

C. TEST SPECIMEN PREPARATION FOR PLASTIC BEAD BLAST PAINT REMOVAL

1. Pretreatment, Coating and Curing of Aluminum Test Panels

(a) The panels were alkaline detergent cleaned using MIL-C-25769 material.

(b) The panels were deoxidized using material conforming to MIL-C-38334.

(c) The panels were chemical conversion coated using material conforming to MIL-C-81706 and applied in accordance with MIL-C-5541.

(d) The panels were primer coated to a dry film thickness of 0.0006 to 0.0009 inch with epoxy primer conforming to MIL-P-23377.

(e) The panels were topcoated to a dry film thickness of 0.0017 to 0.0023 inch with polyurethane paint conforming to MIL-C-83286B.

(f) The panels were cured at ambient conditions of 75°F and 50±5% RH for seven days.

(g) After seven days of ambient cure, the panels were baked at 210°F±2°F for 96 hours.

2. Graphite/Epoxy Composite Panels

(1) The peel ply was removed.

(2) The panels were immediately primer coated to a dry film thickness of 0.6 to 0.9 mils with epoxy primer conforming to MIL-P-23377.

(3) The panels were topcoated to a dry film thickness of 1.7 to 2.3 mils with polyurethane paint conforming to MIL-C-83286B.

(4) The panels were cured for seven days at ambient conditions of 75°F±2°F and 50±5% RH.

(5) After ambient conditioning, the panels were cured at 210°F±2°F for 96 hours.

D. EQUIPMENT AND PROCEDURES USED FOR PLASTIC BEAD BLAST REMOVAL OF PAINT FROM METAL AND COMPOSITE PANELS

1. The abrasive blasting machines used for plastic bead blast paint removal from the test panels were standard commercially available equipment and were being used by personnel at the Ogden ALC to remove paint from F-4 aircraft wing folds.

2. The nozzle size on the abrasive blasting machine abrasive delivery hose was 3/8-inch diameter which was the size nozzle used for plastic bead blast paint removal from F-4 aircraft wing folds and was used for paint removal from the test panels.

3. The plastic bead abrasive blast material used to remove the paint from the panels was the same that was being used to remove paint from F-4 aircraft wing folds. The material is manufactured by U.S. Plastics and Chemical Co. and trade named "POLYPLUS". The plastic bead material has a Moh hardness of 3.5 to 4.0. The plastic bead grit size used was 30 to 40 U.S. seive size.

4. Two blast pressures (measured at the blast nozzle) were used to blast two groups of test panels. One group of the test panels was blasted with the plastic beads at a nozzle pressure of 38 psi. The second group of test panels was blasted with the plastic beads at a nozzle pressure of 60 psi.

5. The nozzle angle of attack normal to the surface of the panels, nozzle stand-off distances from the surface of the panels, and nozzle travel rate across the surface of the panels were not a standardized operation for paint removal from F-4 aircraft wing folds or the test panels.

6. The following paint/plastic bead blast paint removal schedule was used for the test panels.

a. One group of the aluminum honeycomb panels was painted four times and stripped four times at 38 psi nozzle pressure.

b. One group of the aluminum honeycomb panels was painted four times and stripped four times at 60 psi nozzle pressure.

c. One group of the aluminum honeycomb panels was coated with five coats of paint and stripped once at 38 psi nozzle pressure.

d. One group of the 0.063 inch thick unclad 7075-T6 sulfuric acid anodized panels was coated once and stripped once at 38 psi nozzle pressure.

e. One group of the 0.063 inch thick unclad 7075-T6 sulfuric acid anodized panels was coated once and stripped once at 60 psi nozzle pressure.

f. One group of the aluminum thin skin metal to metal bonded panels was painted four times and stripped four times at 38 psi nozzle pressure.

g. One group of the aluminum thin skin metal to metal bonded panels was painted four times and stripped four times at 60 psi nozzle pressure.

h. One group of graphite/epoxy composite panels was painted four times and stripped four times at 38 psi nozzle pressure.

i. One group of graphite/epoxy composite panels was painted four times and stripped four times at 60 psi nozzle pressure.

E. SURFACE ELECTRICAL CONDUCTIVITY

Surface electrical conductivity measurements were made on the plastic bead blasted anodized panels to determine removal of the anodize coating. Measurements were made in accordance with the procedure shown in Section IV of this report.

F. SURFACE ROUGHNESS

Surface roughness measurements were taken with a Surtronic 3 manufactured by Rank-Taylor-Hobson. Each data point represents an average of ten readings (in microinches) taken every 0.03 inches over 0.30 inches travel of the probe. Three specimens were randomly selected from each set of panels after each paint removal for each blast pressure. Five data points were gathered from each of these specimens. Therefore, the final average for each panel/blast pressure/paint removal cycle represents 15 data points.

G. ALUMINUM FATIGUE TESTS

1. Test Procedure

The fatigue tests were conducted at room temperature in accordance with ASTM Standard Practice E 466-82 using four MTS electrohydraulic servo-controlled testing machines. These tests were axial, tension-tension, constant load amplitude and were controlled by means of a load cell output. The test frequency was constant during each test; however, for all tests it varied between 10 to 22 Hz depending on the test machine used and the expected cycles to failure. A stress ratio (R = minimum stress/maximum stress) of 0.3 was used for the thin skin honeycomb tests and 0.1 for the anodized aluminum sheet tests. The test loads for the thin skin honeycomb specimens were calculated using a nominal thickness of 0.016 inch and those for the anodized aluminum sheet specimens were calculated using the measured thickness from each specimen.

2. Test Specimen Geometry and Machining

a. Thin Skin Aluminum Honeycomb

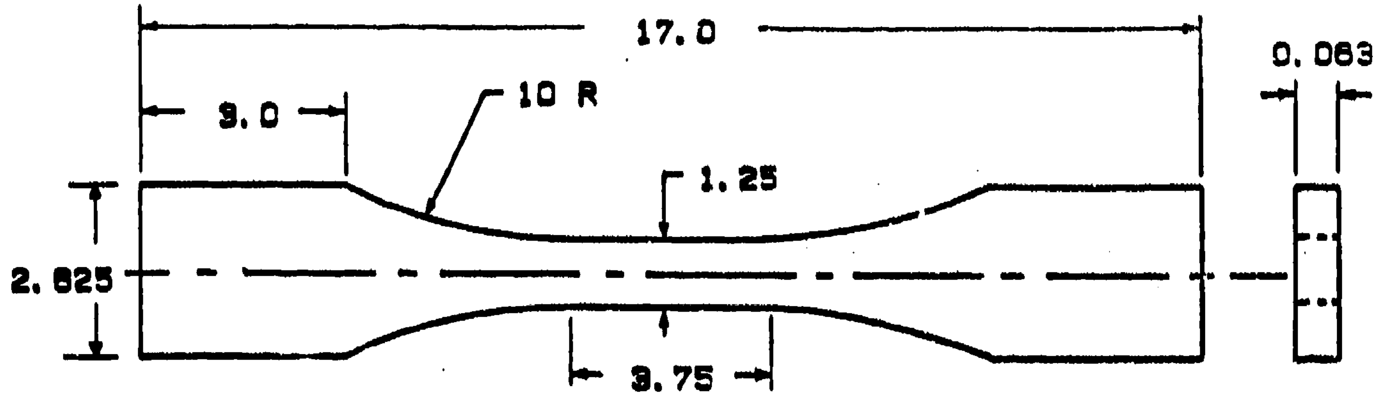
The specimen geometry shown in Figure 1b was used for fatigue testing of the thin skin aluminum honeycomb material. The specimens were machined from 24 inch by 4 inch panels using a Bridgeport milling machine having a paper tape programmer and digital-depth-of-cut setting. The flat face sheets of the specimens remained in the as received condition or the plastic bead stripped condition. These specimens were machined using one roughing cut leaving 0.020 inch of material per machined edge. Prior to cutting the machined panels along the center of the honeycomb core, the final 0.020 inch of material was removed as discussed in the next paragraph.

For the baseline specimens, and for specimens up to the third paint removal, the final 0.020 inch of material was removed in one step. The edges were then manually sanded longitudinally using 320 grit silicon carbide paper. However, this machining procedure produced some early fatigue failures. Examination after testing revealed that on some of the specimens the alclad had formed a lip or burr along part of the machined edges. On some specimens, these lips were found to be fatigue crack initiation sites. Therefore, beginning with the specimens from the third paint removal, the outside edge corners (alclad side) were slightly rounded using 600 grit silicon carbide paper. It was then found that for some of these specimens that the crack initiations occurred along the machined edge at material raised up on the honeycomb side of the specimen. For the fourth paint removal specimens, the last 0.020 inch of material was removed in six steps. The final 0.003 inch of stock per side was removed at a rate of 0.001 inch per cut. The edges were sanded longitudinally and the outside edge corners rounded as above.

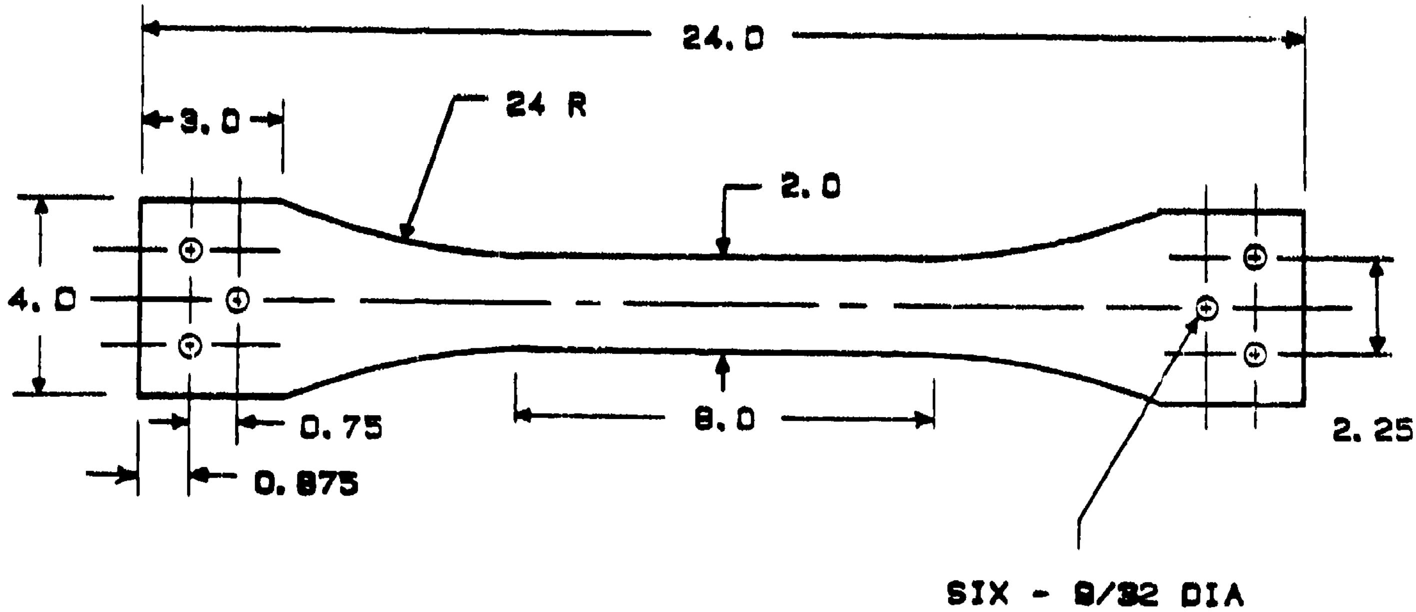
All of the honeycomb sandwich machined panels then were cut down the center of the one-half inch thick honeycomb core to provide two test specimens from each panel. The final machining step was to mill away the honeycomb material at both ends of the specimens to allow aluminum tab material to be applied to the thin skin aluminum. This procedure also caused some early failures because too much of the 0.016 inch face skin was removed along with the honeycomb core. Aluminum tabs were bonded on the ends of the test specimens using FM-300 epoxy film adhesive and cured at 215°F for two hours. All of the specimens that failed due to the above mentioned machining flaws are noted in the data.

b. Sulfuric Acid Anodized Unclad Aluminum Sheet

These test specimen blanks, 2.625 inches by 17 inches by 0.063 inches of unclad 7075-T6 aluminum were removed from four foot wide sheets. The blanks were sulfuric acid anodized and dichromate sealed in accordance with Type II of Specification MIL-A-8625. The specimens were then machined to the configuration shown in Figure 1a using the previously discussed milling machine having a paper tape numerical control. The roughing cut for these specimens left 0.025 inch of material per edge. This remaining material was removed in seven steps. The final



a. Unclad Aluminum Sheet Specimen



b. Thin Skin Aluminum Honeycomb Specimen

Figure 1. Aluminum Fatigue Specimen

0.004 inch of stock per side was removed at a rate of 0.001 inch per cut. The machined edges of these specimens were polished longitudinally using 600 grit silicon carbide paper. Aluminum tabs were also bonded to the ends of these specimens.

H. METALLOGRAPHY

Metallography was performed to evaluate the surface finishes and properties of metallic materials subjected to plastic bead paint removal. What follows is a description of the metallographic techniques employed in this particular program. These techniques parallel those outlined in Section IV "Guidelines for Evaluating the Effects of Plastic Bead Paint Stripping on Metallic Materials."

Specimen selection was dictated by a general plan which was devised to maximize the information gained while minimizing the time, effort and materials needed to conduct the metallographic evaluation. Basically, specimens were selected to represent a particular test condition. For instance, specimens were selected based on the nozzle pressure used during paint removal and the maximum stress level used during fatigue testing. Therefore, at least four specimens were prepared for metallographic analysis for each paint removal operation performed on the thin skin aluminum specimens: one specimen at 38 psi nozzle pressure, 32 ksi maximum fatigue stress; one specimen at 38 psi, 45 ksi; one at 60 psi, 32 ksi; and one at 60 psi, and 45 ksi. Sometimes the specimens were selected to represent the test conditions and to determine why some fatigue specimens failed prematurely. In any event, the specimens were selected to extract the most information with the minimum of effort.

Once a particular fatigue specimen was selected for metallographic analysis, a sample was excised from the fatigue specimen within one inch of the fracture surface of a failed fatigue specimen and from within the gage section of the unfailed fatigue specimen. Sheet metal shears were used as a "first cut" in sectioning the metallographic specimen from the thin skin aluminum fatigue test specimens and a band saw was used for the 0.063 inch thick specimens. Then, both the metallographic and fractographic specimens were carefully sectioned using a diamond cut-off wheel. Since the thin skin aluminum honeycomb material could not be mounted squarely in the metallographic mount, the metallographic specimen was soaked in a ketone solvent to dissolve the adhesive bonding the honeycomb to the thin aluminum sheet. This was accomplished by placing the metallographic specimen in a beaker and with enough solvent to just cover the specimen. The beaker was then placed in a warm water bath (120°F) to speed the honeycomb stripping process. After stripping the honeycomb from the aluminum skin, the specimen was rinsed with water and methanol and then dried. Once these steps were completed the specimen was mounted.

After grinding and polishing the metallographic mounts, the specimens were then etched with Nital for 20 seconds, rinsed with water, rinsed with methanol, and blown dry with compressed air. Then the mount was lightly run around the 0.05 micron alumina polishing wheel and then re-etched as above. This technique revealed greater detail than just a single etch process. Once properly prepared, the metallographic specimen was ready for analysis.

A standard metallograph was used to evaluate the effects that plastic bead paint removal had on the aluminum specimens. Special attention was given to the side of the specimen from which paint had been removed; the unpainted side (the honeycomb side) was used for comparison. Photomicrographs were taken at 160x and 800x.

I. FRACTOGRAPHY

Fractography was performed on some of the failed fatigue specimens which were subjected to plastic bead paint removal. Both light optical and electron fractography were performed on the specimens with two goals in mind. The first was to determine where the fracture initiated and the second was to determine if plastic bead paint removal was responsible for initiating the crack. Like the metallographic analysis, the fractographic analysis was based on Section IV, "Guidelines for Evaluating the Effects of Plastic Bead Paint Removal on Metallic Materials." What follows is a description of the salient features associated with conducting the fractographic analysis.

All of the failed fatigue specimens were subjected to light optical fractography while some required additional electron fractography. The light optical fractography was conducted to determine the approximate location of the fracture initiation site. If the initiation site was not at the edge or corner of the specimen, then the specimen was considered for electron fractography. Typically, all of the premature failures were scrutinized in the scanning electron microscope while only some of the baseline specimen failures were examined.

Once a particular specimen was selected for electron fractography (due to its fatigue life or its initiation site) the specimen was prepared for further examination. The first step was to carefully remove the fracture face from the rest of the fatigue specimen. Sheet metal shears were used on the thin skin honeycomb specimens and a band saw was used on the 0.063 inch thick specimens. Fractographic sectioning was performed in the same way as the metallographic sectioning and, in many cases, metallographic and fractographic specimens were removed from the failed fatigue specimen in one cut. After removing the fracture face from the fatigue specimen, the fracture face was sectioned using a diamond cut-off wheel to further reduce the specimen size so that it could fit in the scanning electron microscope. The specimen was then rinsed with methanol and then cleaned with acetone in an ultrasonic bath. It was not necessary to remove the honeycomb core material from the thin skin aluminum specimens. After cleaning, the specimens were affixed to aluminum stubs with a carbon adhesive.

The fracture faces were then examined using a scanning electron microscope. After examining several specimens a routine was established for evaluating the fracture faces. The first step was to tilt the fracture face so as to view both the fracture face and the plastic bead paint stripped surface at the same time. This technique helped in determining if the initiation site was linked to plastic bead paint removal. If this was true, then the specimen was examined more thoroughly.

J. BOND STRENGTH OF ALUMINUM THIN SKIN METAL TO METAL BONDED PANELS

1. Test Procedure

The peel resistance of the adhesive (T-peel test) was determined in accordance with ASTM Test Method D1876-72.

2. Test Panel Preparation and Geometry

The bonded panels were 12 inches by 12 inches in size. After each paint/paint removal cycle a one inch by ten inch section was sheared from the panels for adhesive peel strength measurements.

K. GRAPHITE/EPOXY COMPOSITE PANELS

1. Test Procedures

The tensile and four point flexure tests were conducted in a 10,000 lbs. capacity Instron testing machine. These tests were performed in accordance with ASTM Test Methods D3039-76 (tensile) and D790-84a, Method II (four point flexure) except that the crosshead speed for all tests was 0.05 inch/minute. The tabbed ends of the tensile specimens were gripped using wedge action grips. Tensile strain was obtained using a two inch Instron clip-on type extensometer.

For the flexural tests, the load fixture was adjusted to either a 2.0 inch or 2.2 inch span which resulted in a span-to-depth ratio of 32:1. Mid-span deflection in the flexure specimens was determined using a deflectometer having a microformer for an electrical output. The majority of the test specimens did have deflections greater than ten percent of the span. Therefore the maximum stress was calculated using the formula given in ASTM D790-84a. When the specimens failed in interlaminar shear rather than in the outer fibers, interlaminar shear strength value was calculated by dividing the maximum tensile stress by the respective span-to-depth ratio (Reference 1).

2. Test Panel Preparation and Geometry

Quasi-isotropic and unidirectional 24 inches by 24 inches 12 ply panels were made with AS4/3501-6 graphite/epoxy prepreg tapes manufactured by Hercules, Inc. The laminates were fabricated in an autoclave according to the manufacturer's recommended cure cycle. A listing of the laminates and fiber orientations is shown in Table B1. The physical property data obtained from the laminates are given in Table 1. After each paint/paint removal operation, straight-sided specimens, tensile and flexure, were cut from the large panels using a diamond impregnated saw. The specimens were one inch by ten inches for the tensile tests and one inch by five inches for the flexural tests. Fiberglass/epoxy end tabs were bonded to the tensile test specimens.

TABLE 1

PHYSICAL PROPERTY DATA [1]

Panel Number	Specimen Group Designation	Laminate Specific Gravity	% Resin Content by weight	% Fiber[2] Content by volume	% Void[2] Content by volume
5	D	1.61	28.9	63.7	0.0
6	F	1.59	30.3	61.8	0.0
7	L	1.56	32.9	58.2	1.1
8	M	1.59	31.2	60.6	0.1
9	E	1.60	32.2	60.1	0.0
14	N & O	1.61	31.4	61.5	0.0

NOTE: (1) All information is an average of three data points per panel.

(2) 1.26 g/cc resin density and 1.80 g/cc fiber density values were used to calculate fiber content and void content.

SECTION III

RESULTS AND ANALYSIS

A. PANEL QUALITY ASSURANCE

1. Bonded Aluminum Test Panels

As discussed in Section IIB, the bonded aluminum honeycomb panels and the thin skin metal to metal bonded aluminum panels were ultrasonically inspected after each paint removal cycle. No adhesive debonding was detected by ultrasonic inspection in any of the two groups of test panels, one group being blasted at 38 psi nozzle pressure and one group at 60 psi nozzle pressure, after four paint removal cycles. Additionally, T-peel adhesive bond strength was determined on the aluminum thin skin bonded panels which showed no effects. This data is shown in Table 2 and represents the average of three specimens for each pressure and paint removal cycle. The increase in peel strength of the adhesive is attributed to the additional curing of the adhesive during subsequent baking of the panels to heat age the paint. Visual observation of these panels showed warpage due to the cold working of the surface by the plastic bead blast paint removal process. No Almen intensity measurements were made for these panels.

2. GRAPHITE/EPOXY COMPOSITE PANELS

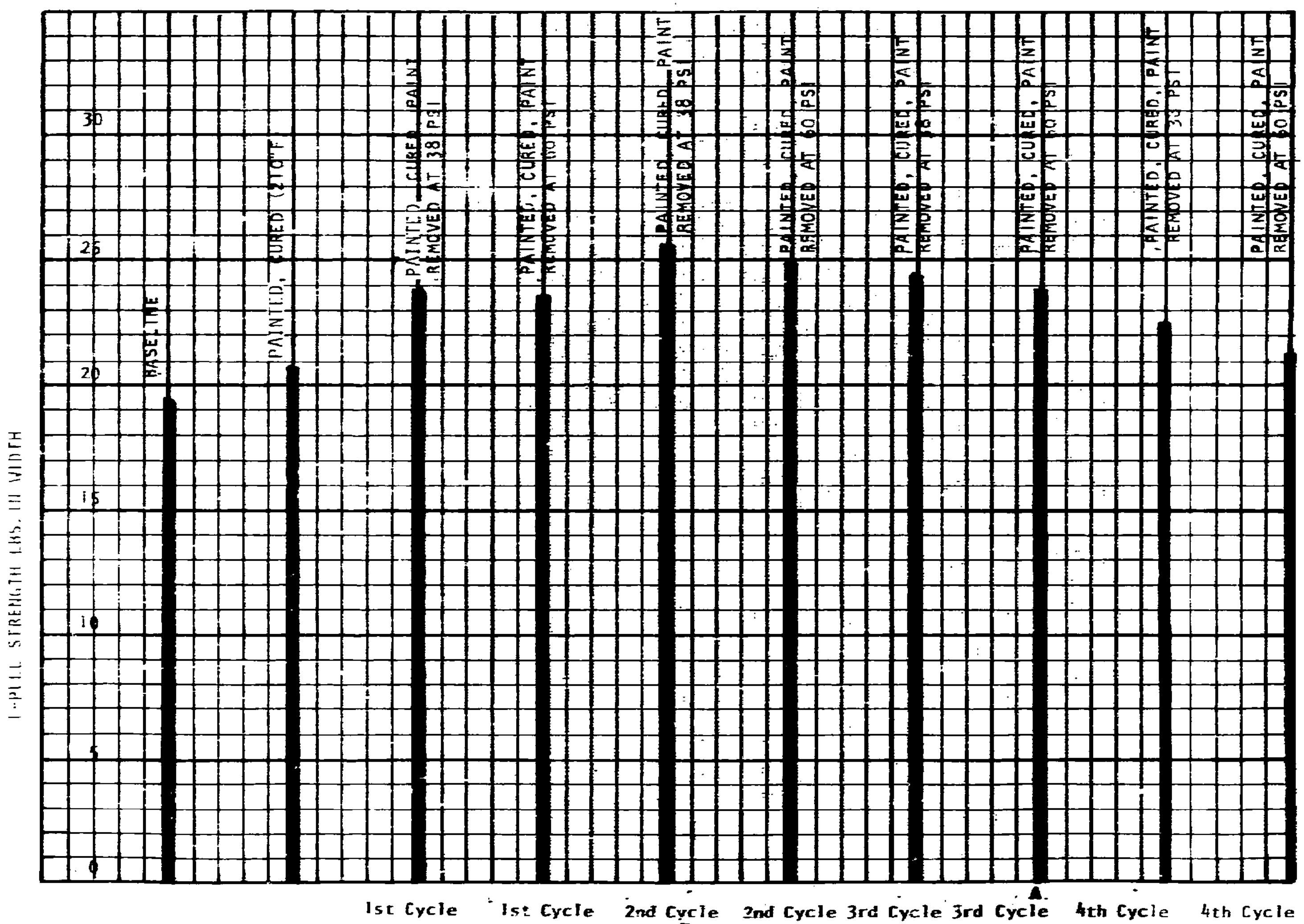
Ultrasonic and x-ray inspection of the composite panels showed no ply debonding or laminate cracking in any of the test panels, even after four paint removal cycles. Visual examination did show gel coat removal and examination by scanning electron microscope showed fiber/matrix debonding and matrix cracking which will be discussed later in this report.

B. SURFACE ELECTRICAL CONDUCTIVITY

Surface electrical conductivity measurements were made on all anodized aluminum test panels initially to ensure a continuous anodized coating in accordance with the surface electrical conductivity measurement procedure shown in Section IV. All of these anodized test panels showed infinite surface resistivity. After one

TABLE 2

T-PEEL STRENGTHS OF PLASTIC BEAD BLASTED THIN SKIN ALUMINUM METAL TO METAL-BONDED PANELS



plastic bead blasting of the chromic acid anodized and sulfuric acid anodized test panels at either nozzle pressure, all anodized panels showed infinite surface conductivity. These results indicate that the anodized coating was removed by the plastic bead blast paint removal process.

C. SURFACE ROUGHNESS

Surface roughness on aircraft metallic structure is of concern from the standpoint of both aerodynamic drag and the effects on mechanical properties such as fatigue. Measurements of the surface roughness in microinches of two separate test panel groups of 0.016 inch thick anodized alclad 7075-T6 aluminum sheet (one group blasted at 38 psi nozzle pressure and one group at 60 psi nozzle pressure) for four successive paint removals showed peak surface roughness of 184 microinches after the first paint removal. The surface roughnesses of each test group of panels which were plastic bead blasted at 38 psi and 60 psi nozzle pressure respectively decreased progressively with three successive plastic bead blastings to 75 microinches. This progressive decrease in surface roughness shows that some alclad is removed each time the surface is plastic bead blasted. The surface roughness data is shown in tabular form in Table 3 and graphically in Table 4. Shown also in Table 3 are surface roughness values for the panels coated after each paint removal with the standard Air Force exterior aircraft finish which is 0.0006 inch to 0.0009 inch dry film thickness of epoxy primer conforming to MIL-P-23377 and 0.0017 inch to 0.0023 inch of polyurethane topcoat conforming to MIL-C-83286. This coating of the plastic bead blasted surfaces decreased the surface roughness to an acceptable level because of the thin cladding on the 0.016 inch thick aluminum sheet material. However, higher surface roughness will occur on aluminum material having greater thickness, which will also have a greater thickness of soft cladding. The effects of surface roughness will have to be assessed for each weapon system based on final roughness after paint application and the total critical surface area.

D. FATIGUE - ALUMINUM MATERIAL

All of the fatigue data generated during the program are given in Appendix A. These data are presented in Figures A1 to A14 and Tables A1 to A5.

TABLE 3

SURFACE ROUGHNESS MEASUREMENTS - (MICROINCHES)

MATERIAL	REMOVAL PRESSURE	INITIAL ROUGHNESS		AFTER 1st REMOVAL		RECOATED SURFACE AFTER 1st REMOVAL		AFTER SECOND REMOVAL		RECOATED SURFACE AFTER 2nd REMOVAL		AFTER THIRD REMOVAL		RECOATED SURFACE AFTER 3rd REMOVAL		AFTER FOURTH REMOVAL		RECOATED SURFACE AFTER 4th REMOVAL	
		RANGE	AVG	RANGE	AVG	RANGE	AVG	RANGE	AVG	RANGE	AVG	RANGE	AVG	RANGE	AVG	RANGE	AVG	RANGE	AVG
Honeycomb	-	33-53	43																
	38 PSI			136-181	155	50-89	62	114-194	140	84-139	100	102-142	117	109-136	115	68-96	85	67-95	85
	60 PSI			93-200	149	57-86	67	91-157	123	69-114	97	82-122	109	98-127	114	46-98	82	50-102	76
Metal to Metal Bonded Panels	-	4-12	7																
	38 PSI			47-330	159	51-79	64	106-140	121	88-120	100	101-114	106	142-183	160	56-98	77	54-104	79
	60 PSI			62-384	184	49-75	62	101-146	116	69-103	85	80-120	100	89-120	104	46-94	75	43-103	75

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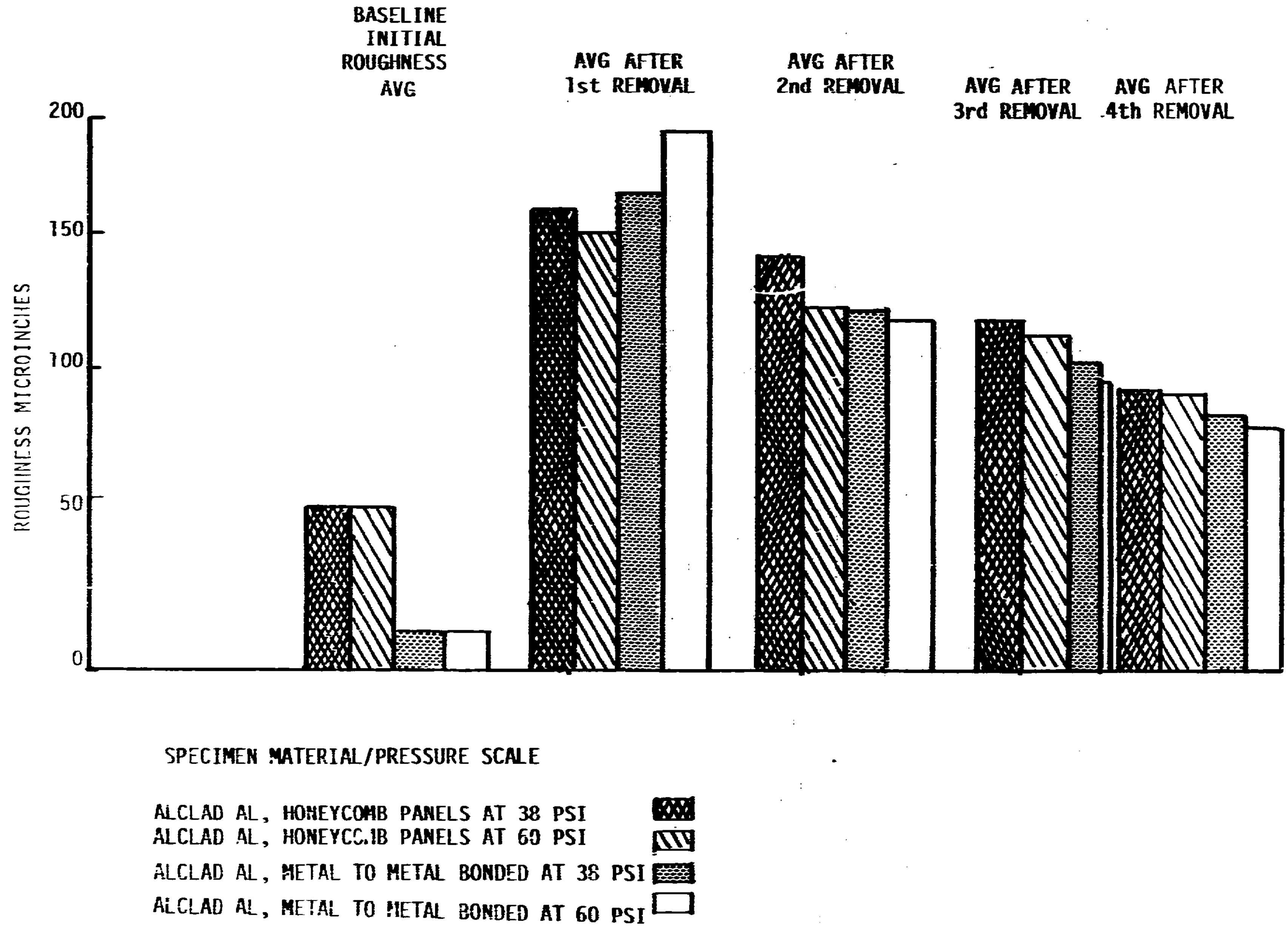
TABLE 4

SURFACE ROUGHNESS MEASUREMENTS (MICROINCHES)



1. Thin Skin Aluminum Honeycomb

The baseline fatigue data obtained from the 7075-T6 alclad thin skin aluminum honeycomb specimens are shown in Table A1 and Figure A1 and Figure 2. One of the curves shown in these figures (which is a reasonable fit to the lowest life data points) was obtained from information available to AFWAL/MLS from the A-10 aircraft structures program from Fairchild Republic, 1973.

Also shown in Figure 2 is the lower 95% confidence curve which was constructed using the procedures given in ASTM standard practice E739-80. A linear best fit equation was obtained using the log stress - log cycles to failure data in the range of stress between 34 to 50 KSI. Rather than showing the 95% confidence bands per ASTM 739-80, only the lower curve was determined since the concern in this program was early failures.

The lower 95% confidence curve and the lower bound curve to the baseline data are shown in Figures 3 to 6 which show the fatigue data after one to four plastic bead paint removals at 38 psi and 60 psi nozzle pressures. Any data resulting from questionable tests, such as failures initiating at machining flaws, handling dents, or at grip ends were excluded from these figures. Data which fell below the lower 95% confidence curve, lower cycles to failure, are identified in these figures by specimen number. Table 5 gives a summary of the fatigue results from the alclad thin skin honeycomb material. For the 38 psi nozzle pressure, the accumulating percentage of total tests falling below the lower 95% confidence curve increases with the number of paint removals. However, for the 60 psi nozzle pressure, the accumulating percentage decreases with number of paint removals which suggests that the higher nozzle pressure is less damaging in fatigue. Two possible explanations for this are: (a) for the 38 psi pressure much longer time was required for removing the paint, therefore exposing the specimens to a greater number of foreign particles mixed in the plastic bead media, and (b) the 60 psi pressure may be placing greater compressive surface stresses in the 7075-T6 aluminum similar to a shot peening process.

2. Unclad Aluminum Sheet

The baseline fatigue data generated on bare 7075-T6 sulfuric acid anodized material, 0.063 inch thick, are shown in Table A4 and Figure A12. The

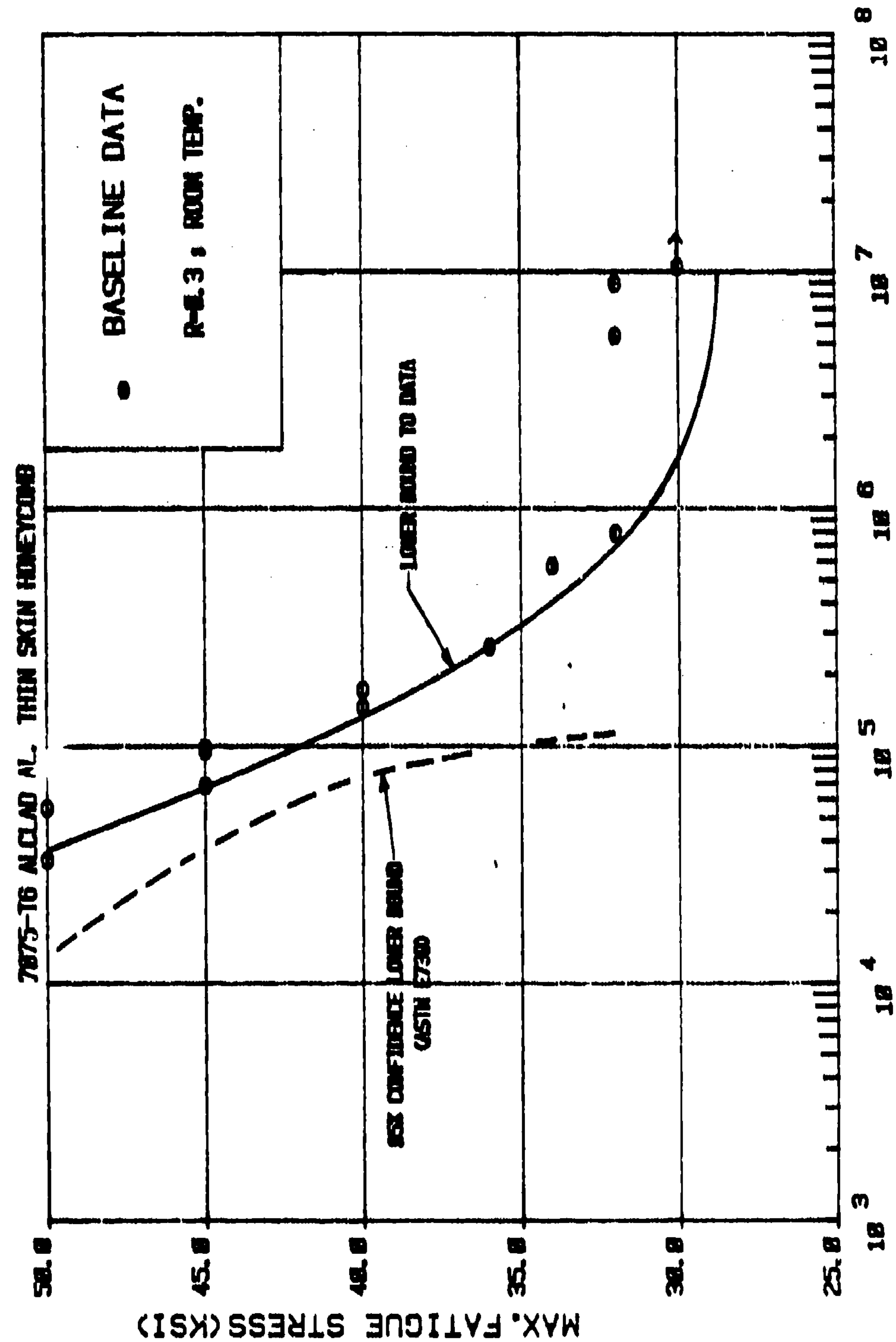


Figure 2. Fatigue Results on 7075-T6 Alclad Aluminum Thin Skin Honeycomb

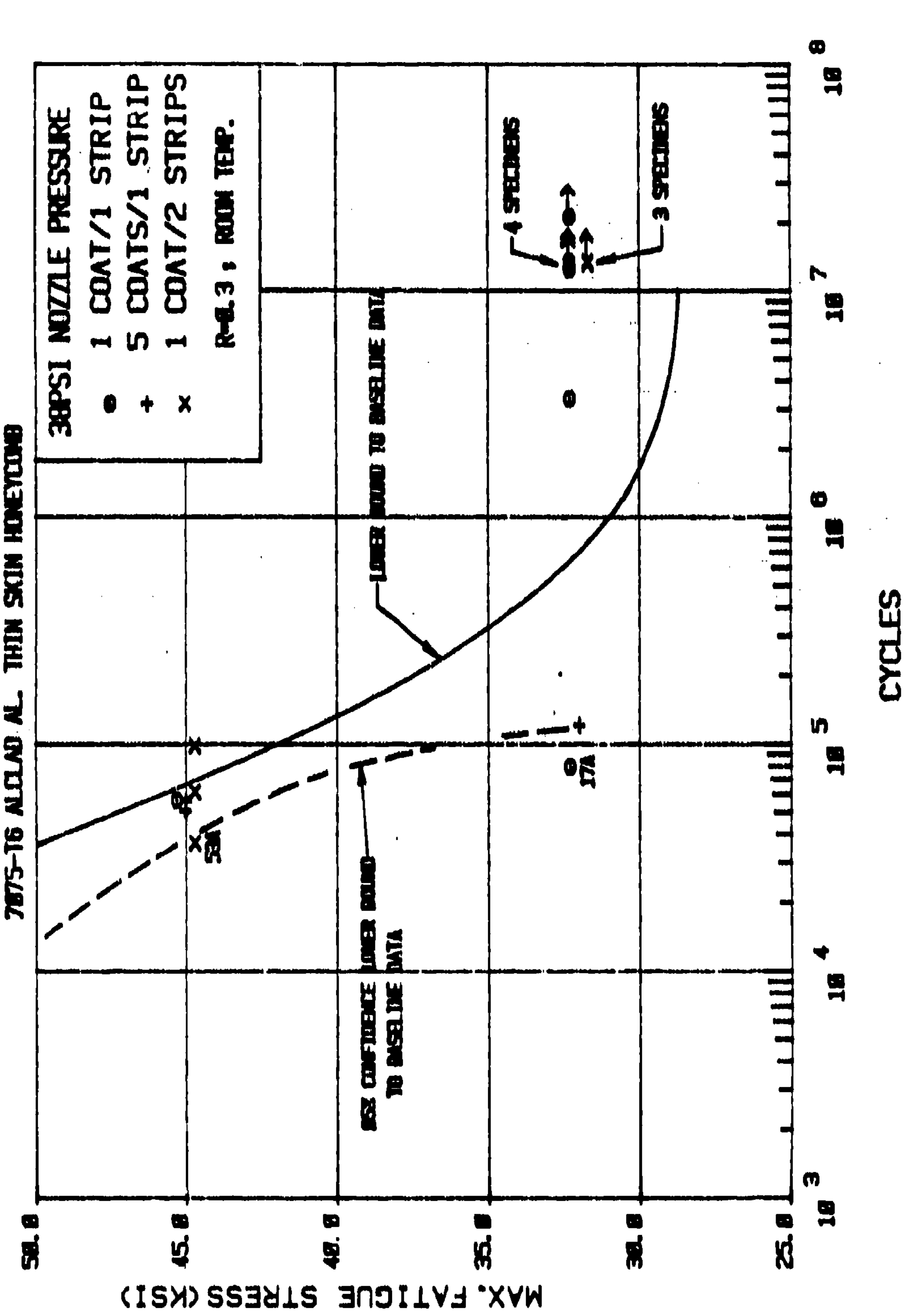


Figure 3. Fatigue Results After One and Two Paint Removals at 38 psi Nozzle Pressure

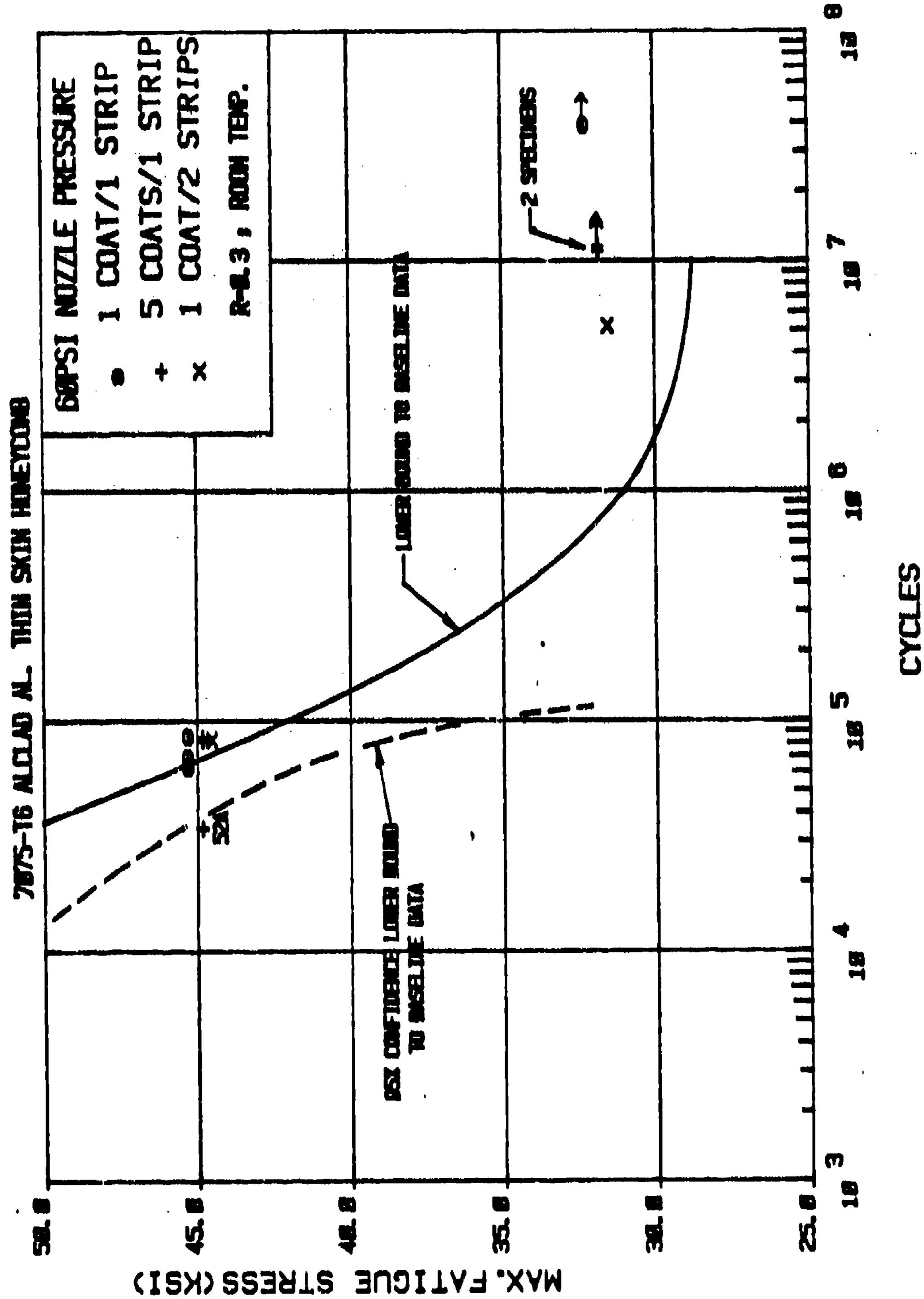


Figure 4. Fatigue Results After One and Two Paint Removals at 60 psi Nozzle Pressure

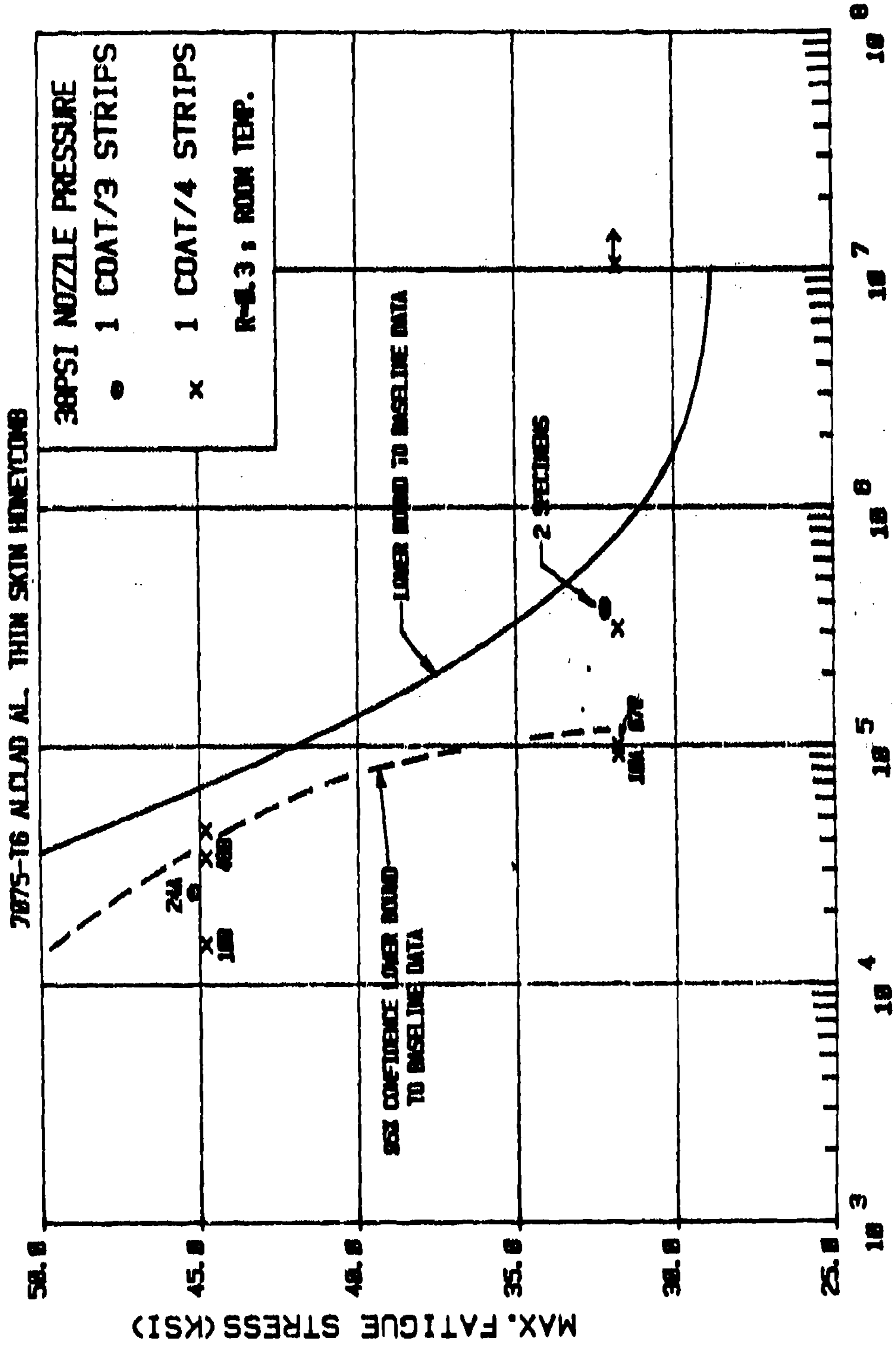


Figure 5. Fatigue Results After Three and Four Paint Removals at 38 psi Nozzle Pressure

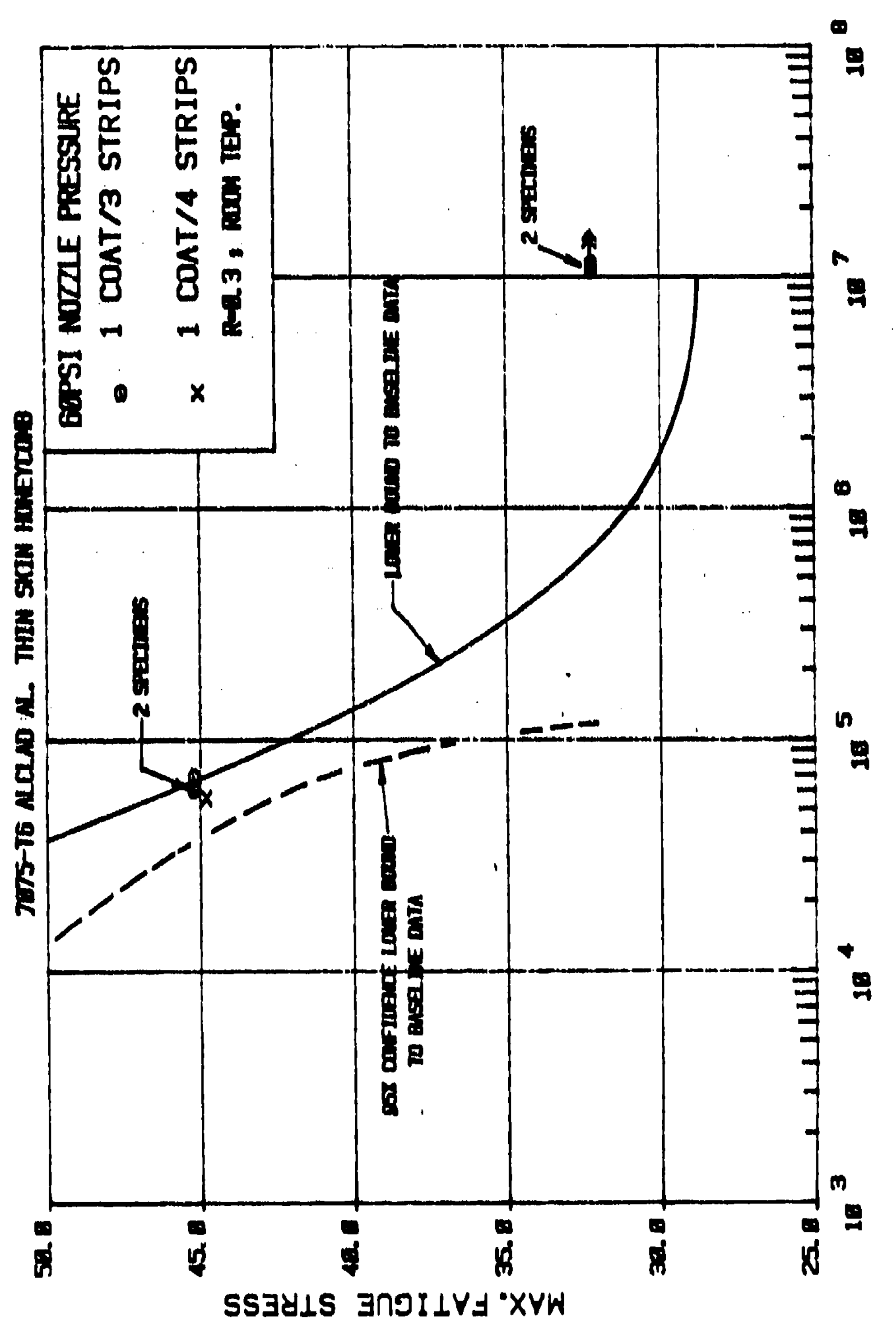


Figure 6. Fatigue Results After Three and Four Paint Removals at 60 psi Nozzle Pressure

TABLE 5

SUMMARY OF FATIGUE RESULTS[1]

(7075-T6 ALCLAD AL THIN SKIN HONEYCOMB)

	1 Paint[2] Removal Cycle		2 Paint Removal Cycles		3 Paint Removal Cycles		4 Paint Removal Cycle	
	38 PSI Pressure	60 PSI Pressure	38 PSI Pressure	60 PSI Pressure	38 PSI Pressure	60 PSI Pressure	38 PSI Pressure	60 PSI Pressure
Total Nr. of Tests	11	9	6	2	3	5	7	1
Nr. That Fall Below Lower 95% Confidence Curve	1	1	1	0	1	0	4	0
Percent of Total Tests	9%	11%	17%	0%	33%	0%	57%	0%
Accumulating Percentages	9%	11%	12%	9%	15%	6%	26%	6%

Notes: (1) Excluded all data resulting from questionable tests such as failures initiating at machining flaws, at possible handling dents, or at grip ends.

(2) Includes data from one paint removal after one and five coats of paint.

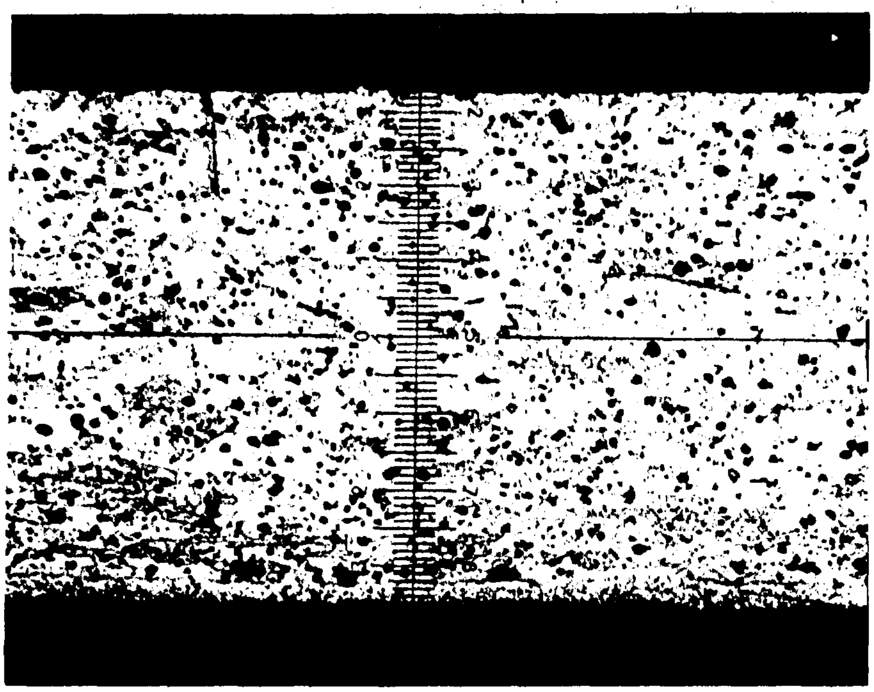


Figure 8. Baseline Alclad 7075-T6. Total thickness 0.016 inch, minimum cladding thickness 0.0005 inch. Kellers etch. MAG: 160X

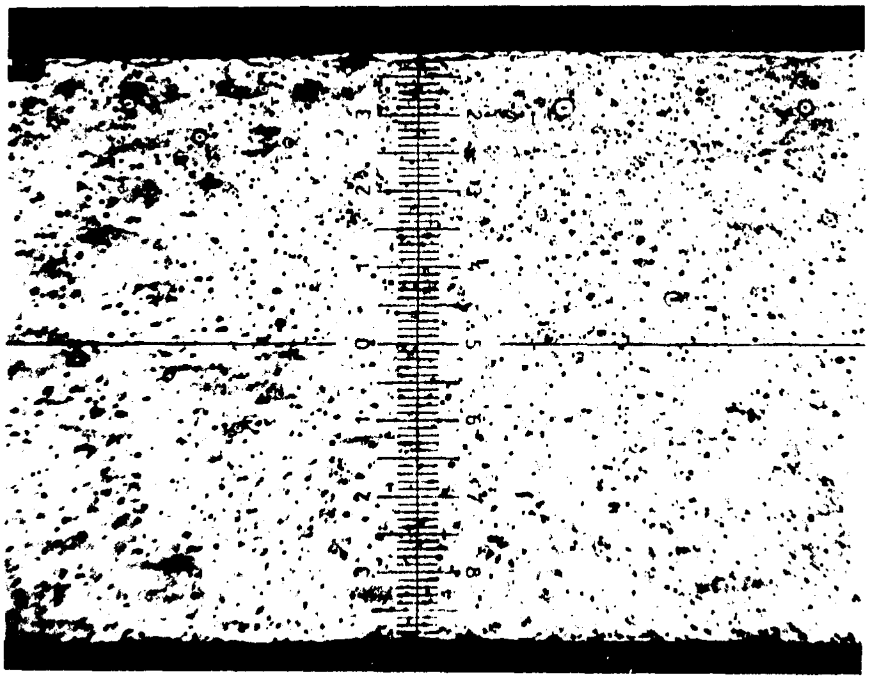
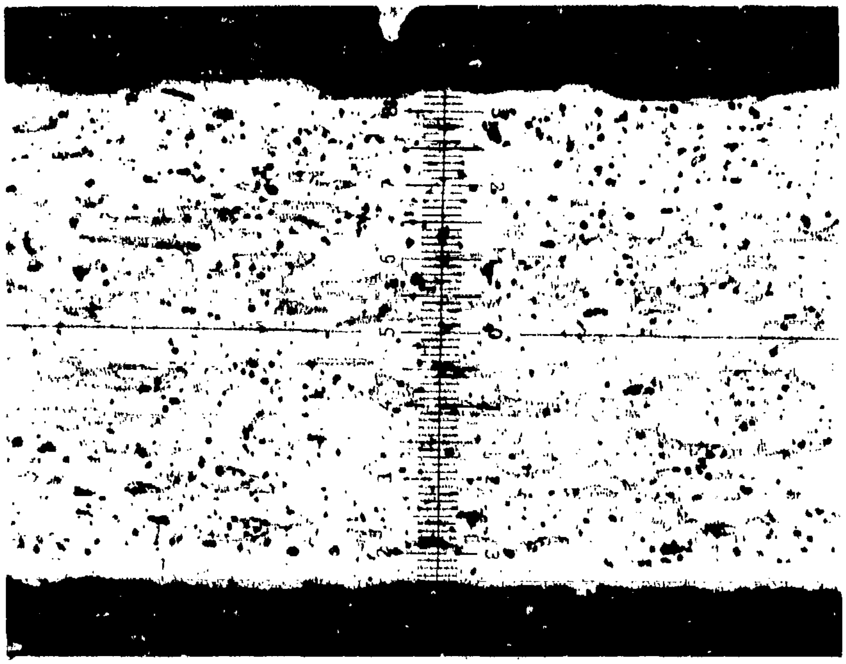
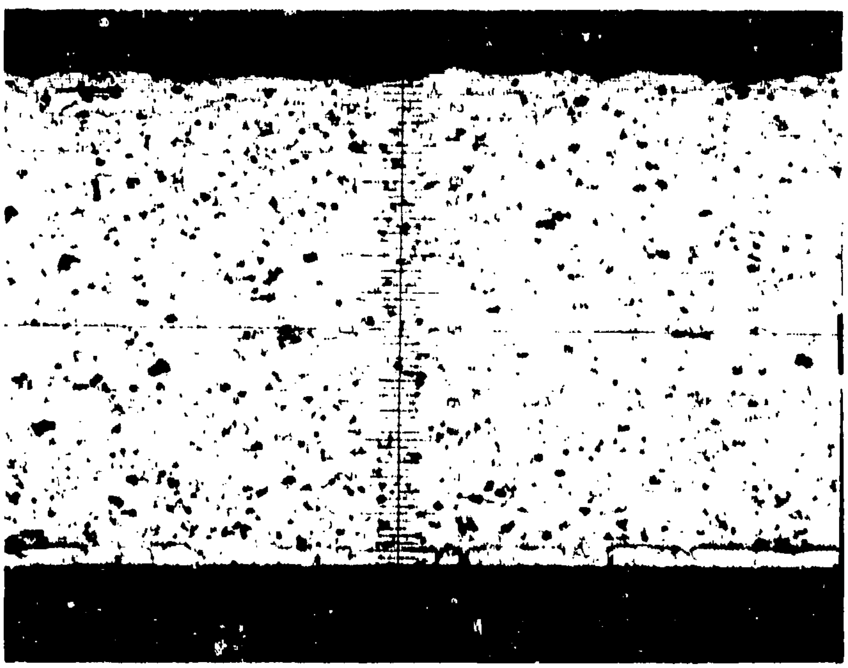


Figure 9. Baseline Sulphuric Acid Anodized 7075-T6, .063 inch thick. Kellers etch. MAG: 100X

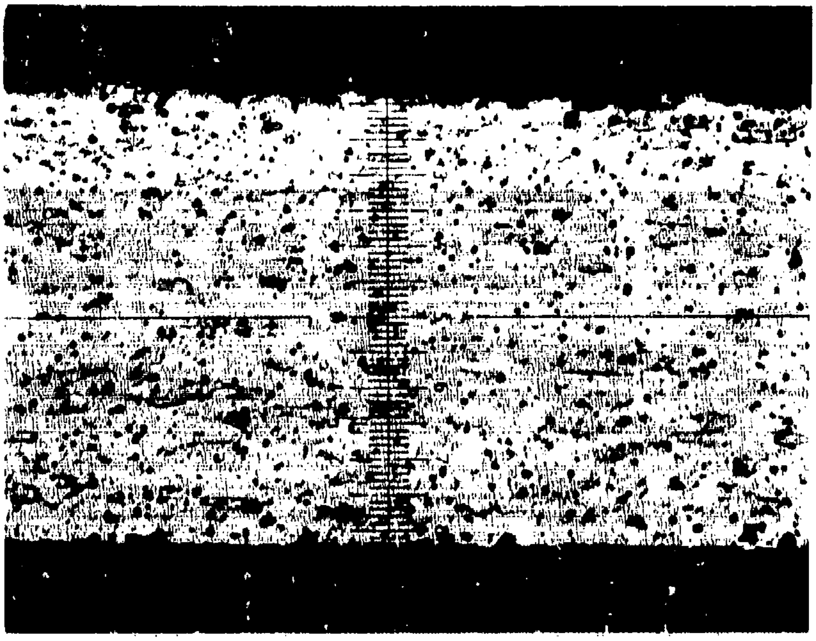


(a)



(b)

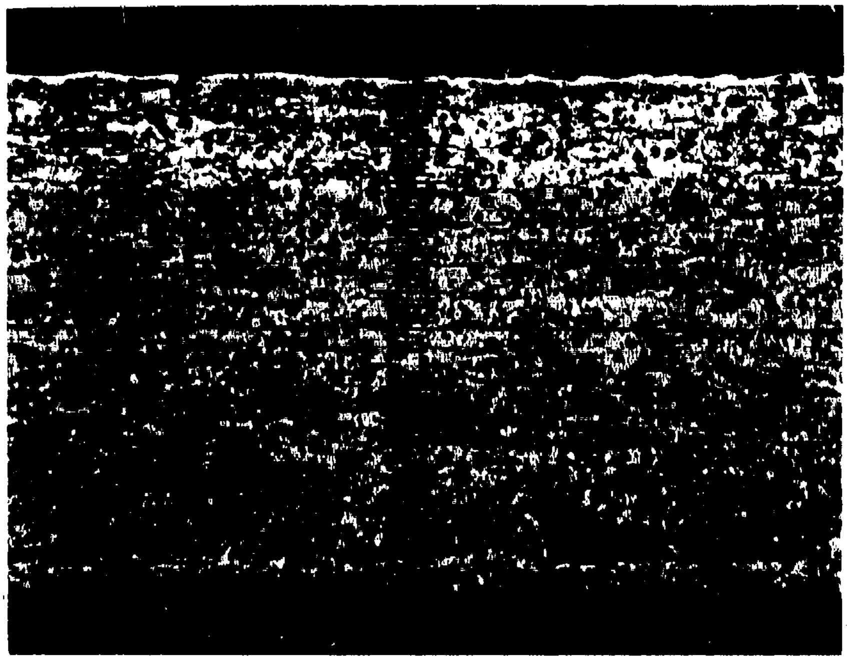
Figure 10. Alclad 7075-T6 After the First Paint Removal. (a) Specimen 17A, 38 psi nozzle pressure, (b) Specimen 13B, 60 psi nozzle pressure. MAG: 100X



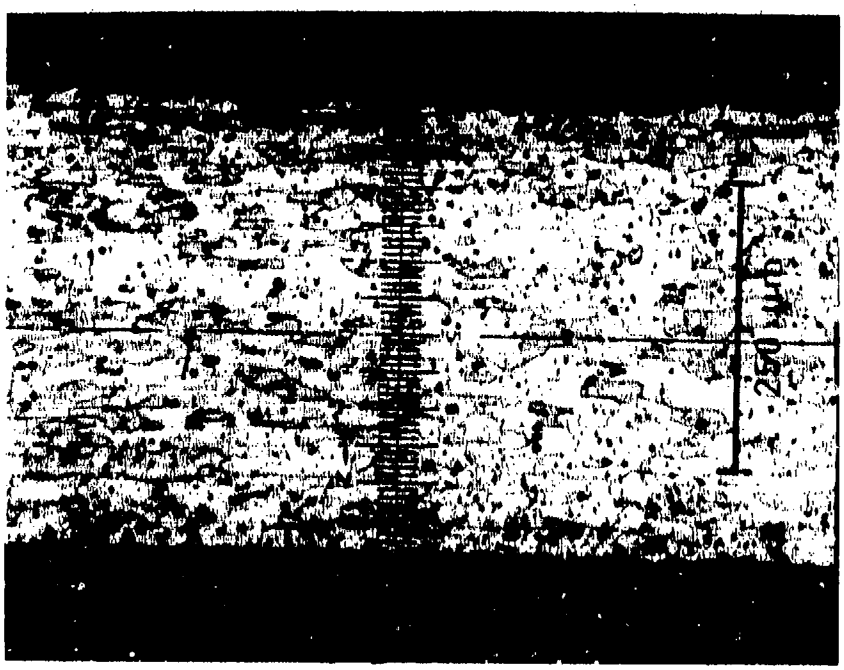
(a)

(b)

Figure 11. Alclad 7075-T6 After the Second Paint Removal on (a) Specimen 53B, 38 psi Nozzle Pressure, (b) Specimen 50A, 60 psi Nozzle Pressure. MAG: (a) 160X. (b) 160X.

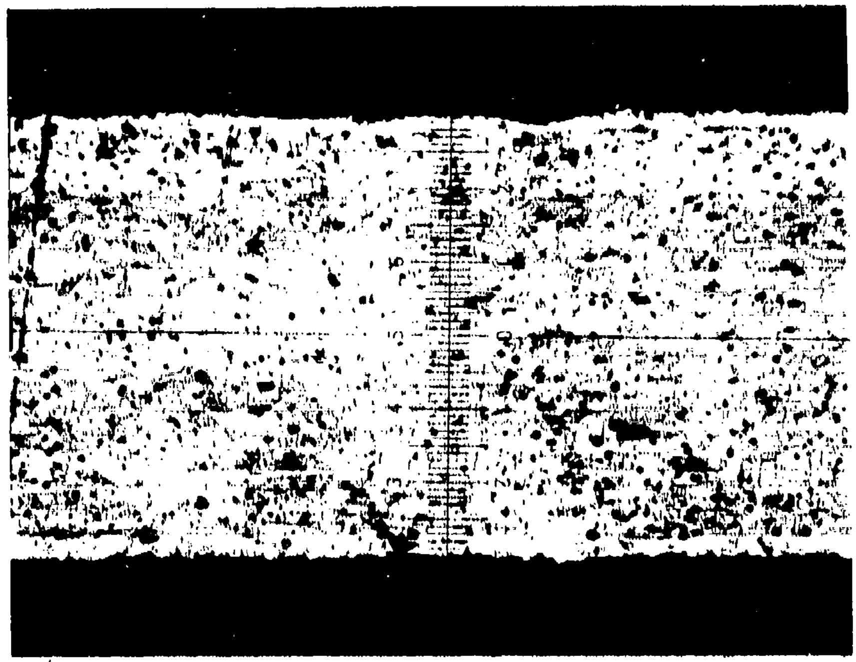


(a)

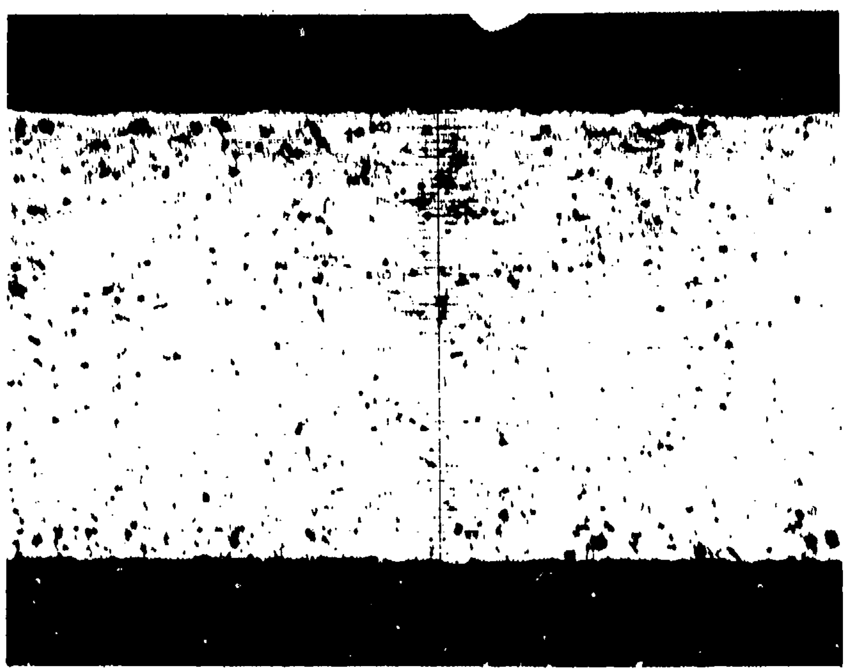


(b)

Figure 12. Alclad 7075-T6 After the Third Paint Removal. (a) Specimen 24B, 38 psi nozzle pressure (b) 60 psi nozzle pressure. MAG: 160X



(a)



(b)

Figure 13. Alclad 7075-T6 After the Fourth Paint Removal. (a) Specimen 10A, 38 psi nozzle pressure, (b) Specimen 35A, 60 psi nozzle pressure. MAG: 160X

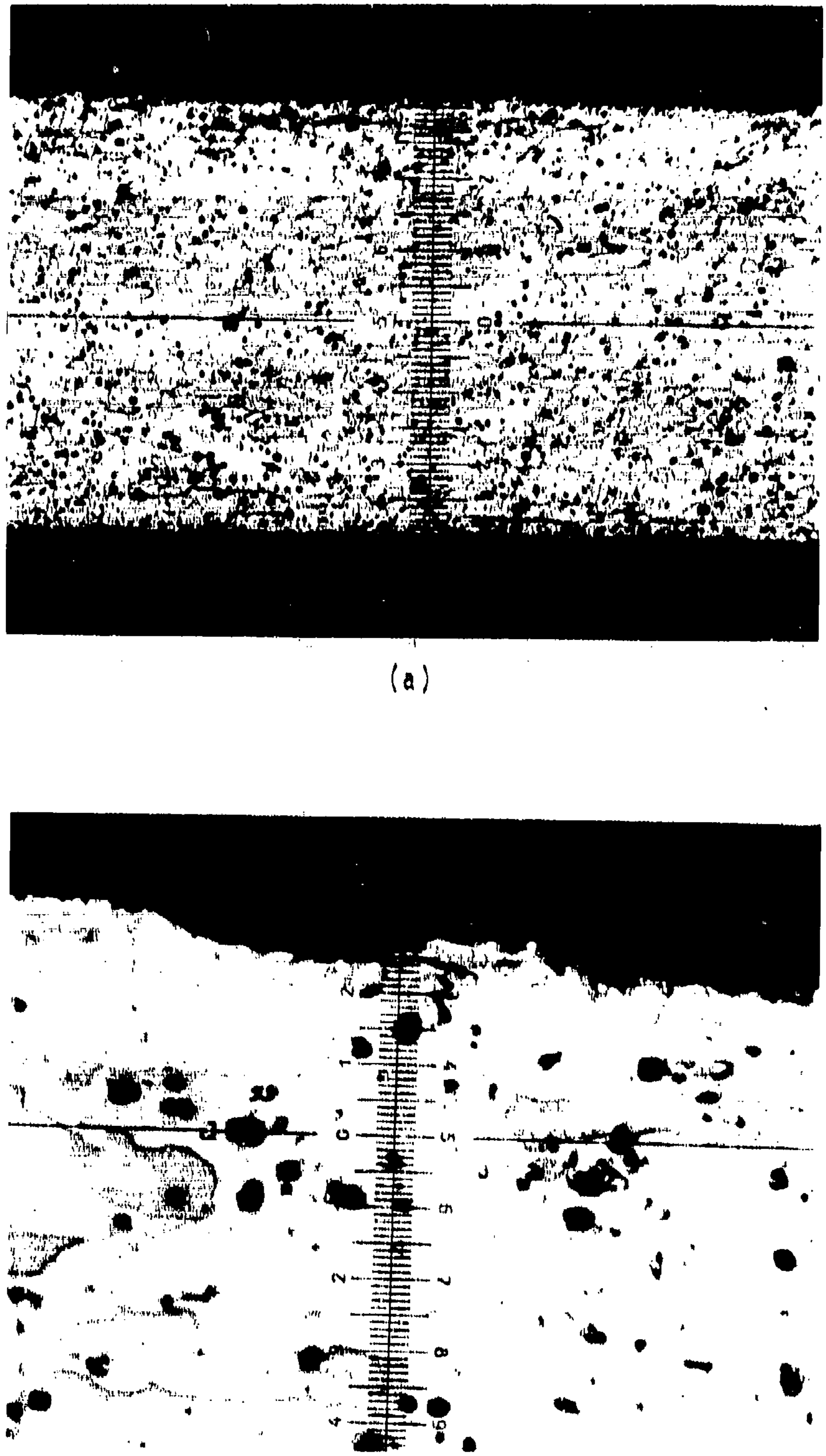
several general observations were made about the effects of plastic bead paint removal. First, the cladding was severely damaged by the paint removal process. The cladding was thinned, cracked, and pitted by the paint removal process. Since the 7072 cladding is very soft, it was very easy for the paint removal process to damage the cladding. Second, the damage produced by the paint removal process was localized and nonuniform. In some areas the cladding was completely removed and in some areas it was not. This was probably due to the variability of the paint removal process. For instance, lower nozzle pressures required longer dwell times than the higher nozzle pressures to remove the same amount of paint. In so doing, the surface was exposed to plastic beads for a longer period of time and increased the likelihood of damaging the alclad. Third, although the thin skin honeycomb panels experienced four paint removal operations, systematic reductions of cladding could not be calculated. That is to say each paint removal operation did not result in a specific reduction of cladding thickness. This was partly due to the localized damage of the paint removal process and the probability of detecting the damage through metallographic analysis. In order to determine the incremental reduction of the cladding thickness for each paint removal operation, exhaustive metallographic and statistical analyses are required which were beyond the scope of this program.

2. Alclad 7075-T6 Thin Skin Honeycomb Panels with Five Coats of Paint and One Paint Removal Operation.

The features found in this portion of the program were similar to those found in the previous section. The cladding was damaged and exhibited pitting, thinning and cracking just as in the sequential paint removal operations described previously. Figures 14 and 15 typify the effects of plastic bead removal of five coats of paint in one operation.

3. Sulphuric Acid Anodized 7075-T6.

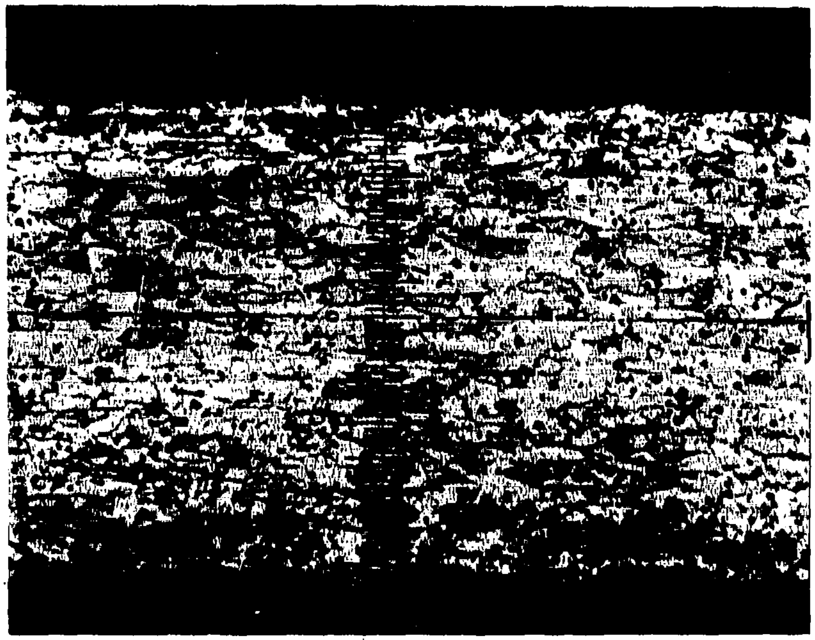
Metallographic analysis indicated that plastic bead paint removal damaged the surface of the sulfuric acid anodized 7075-T6 for either nozzle pressure (Figures 16-18). Some surface pits were detected which measured approximately 0.5 mils across and 0.08 mils deep (Figure 17). Since the unclad 7075-T6 is substantially harder than the alclad 7075-T6 surface, the unclad 7075-T6 was less susceptible to damage by plastic bead paint removal. If anything, it is believed that plastic bead blasting might improve the fatigue properties by peening, thus creating residual



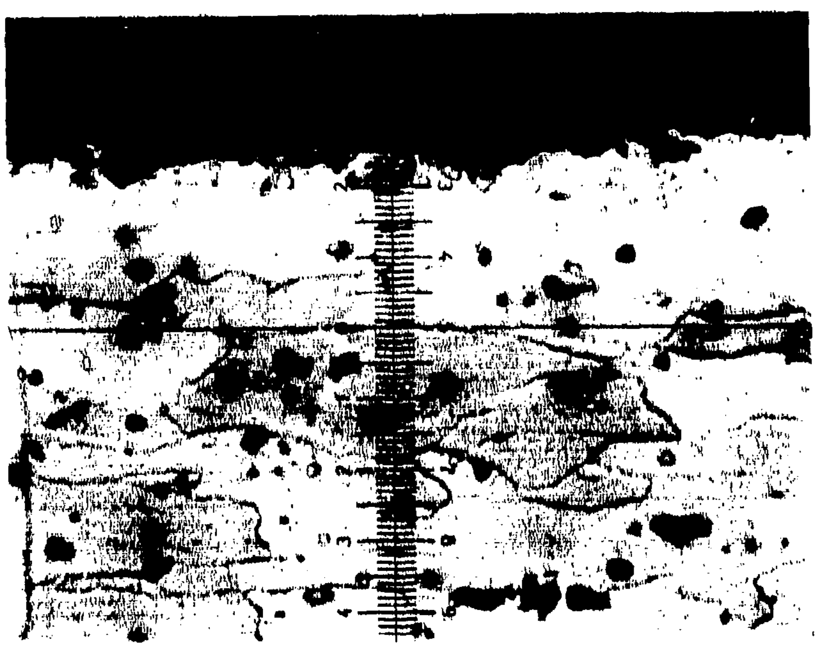
(a)

(b)

Figure 14. Alclad 7075-T6 Thin Skin Honeycomb with Five Coats of Paint After One Paint Removal at 38 psi (Specimen 36A). MAG: (a) 160X, (b) 800X

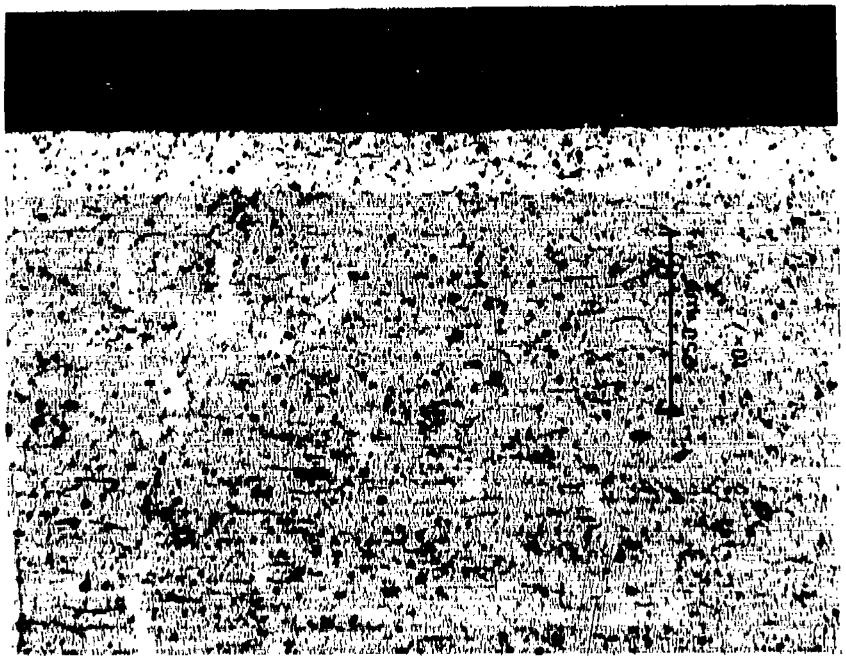


(a)

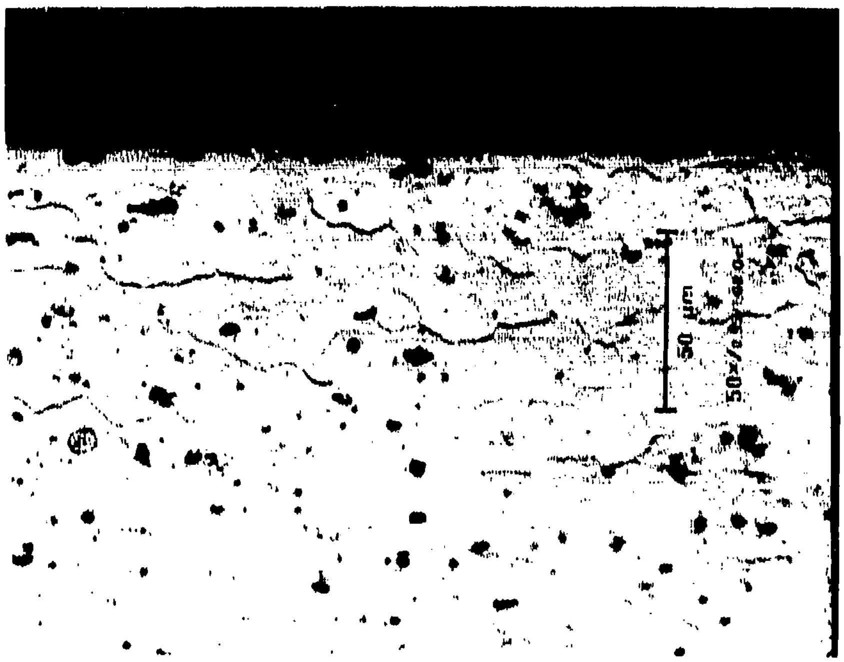


(b)

Figure 15. Alclad 7075-T6 Thin Skin Honeycomb with Five Coats of Paint After One Paint Removal at 60 psi (Specimen 52B). MAG: (a) 160X, (b) 800X

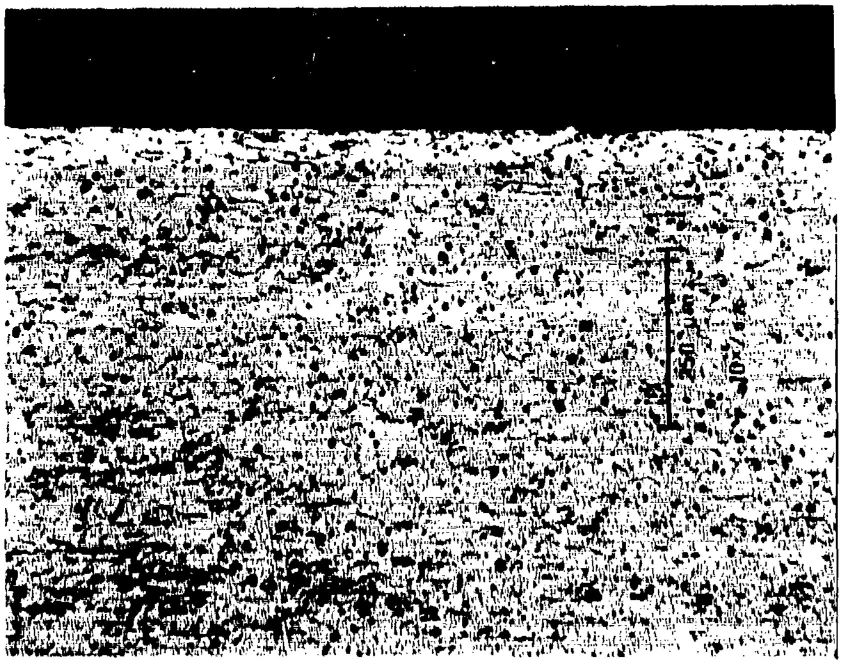


(a)



(b)

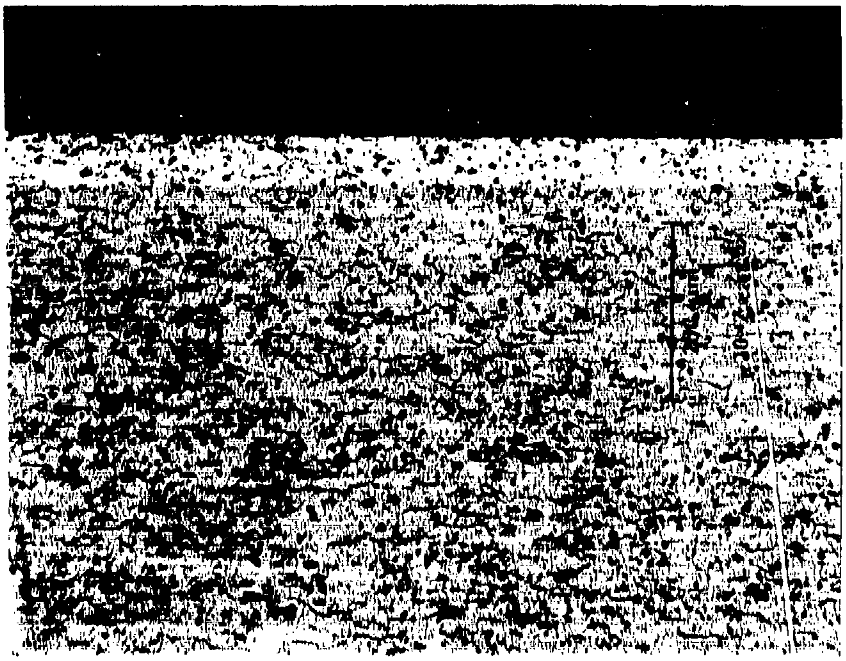
Figure 16. Baseline Sulfuric Acid Anodized 7075-T6. MAG: (a) 100X, (b) 500X



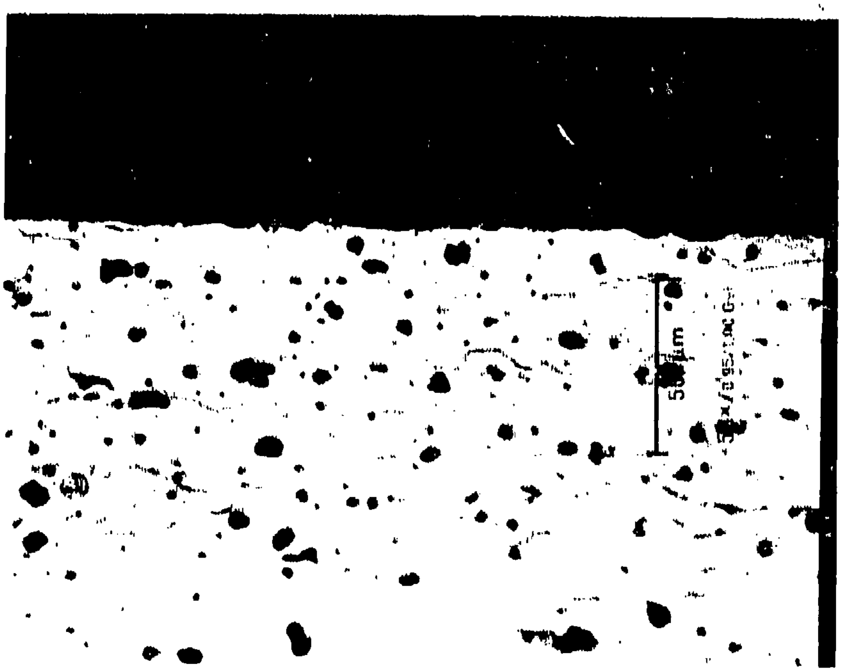
(a)

(b)

Figure 17. Sulfuric Acid Anodized 7075-T6 Blasted with a Nozzle Pressure of 38 psi. MAG: (a) 100X, (b) 500X



(a)



(b)

Figure 18. Sulfuric Acid Anodized 7075-T6 Blasted with a Nozzle Pressure of 60 psi. MAG: (a) 100X, (b) 500X

stresses in the surface. This concept could be investigated at another time. As reported earlier, however, the conductivity tests indicates that the anodized coating was badly damaged or removed even though not obvious metallographically.

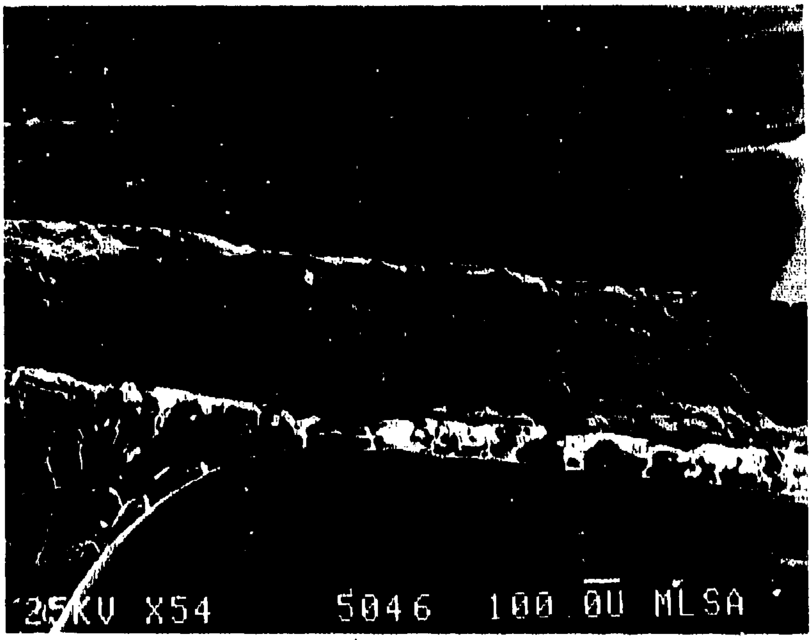
F. FRACTOGRAPHY OF 7075-T6 SPECIMENS

Extensive fractographic analysis was performed on the failed fatigue specimens to determine if plastic bead paint removal was responsible for initiating fatigue failures. The first step in performing the analysis was to examine the fracture surface using light microscopy. If the crack initiation site was not located on the specimen corner or edge, then the fracture face was sectioned and prepared for electron fractography. Specimens failing below the lower bound curves received the most attention. What follows is a description of the salient features of the fractographic analyses performed.

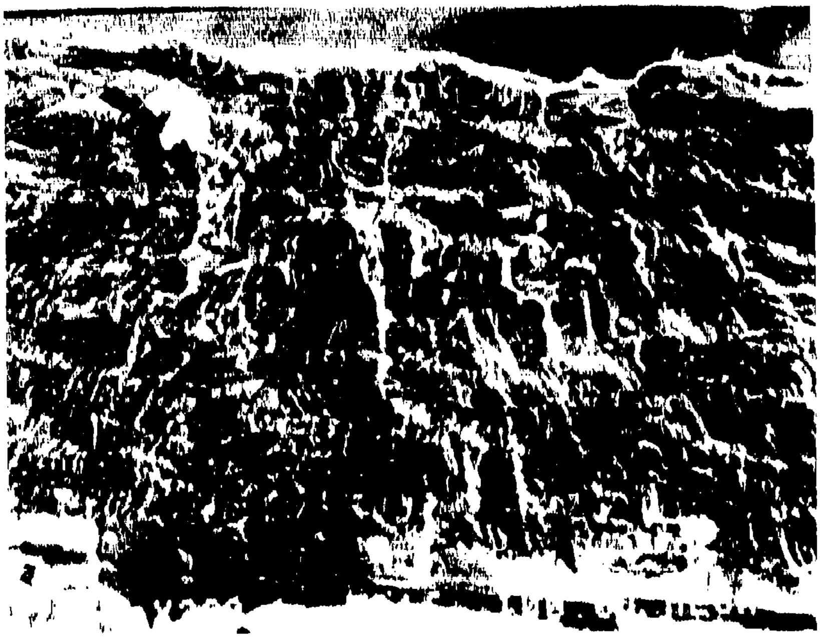
1. Alclad 7075-T6 Thin Skin Honeycomb Panels.

Fractographic analysis of the alclad 7075-T6 thin skin honeycomb panels subjected to four sequential paint removal operations revealed several features.

First, the fatigue crack initiation sites were located either on the plastic bead blasted side, at the corner, or at the edge of the fatigue specimen. Sometimes the specimens failed in the taper radius between the grip and the gage section. Failures in the radius typically initiated at the specimen edge or corner. Regardless of the location of the initiation site, the sites were readily detected optically using low magnifications (2x to 7x). Typical initiation sites as they appeared in the electron microscope are shown at higher magnifications in Figures 19 and 20. Crack initiation sites located on the plastic bead blasted surface were scrutinized while those initiation sites located on the edge or corner received little attention; edge and corner initiation sites are mechanistically favored when compared to surface sites for the specimen configuration used in this program. In order to determine whether or not plastic bead paint stripping effected the fatigue life, only those fatigue initiation sites located on the plastic bead blasted surface could be construed as responsible for affecting the fatigue life. Fractography also revealed that none of the crack initiation sites were located on the honeycomb side of the panel.



(a)



(b)

Figure 19. Typical Surface Initiation Site of an Alclad 7075-T6 Alloy. Specimen 17A, first paint removal at 38 psi. MAG: (a) 54X, (b) 200X

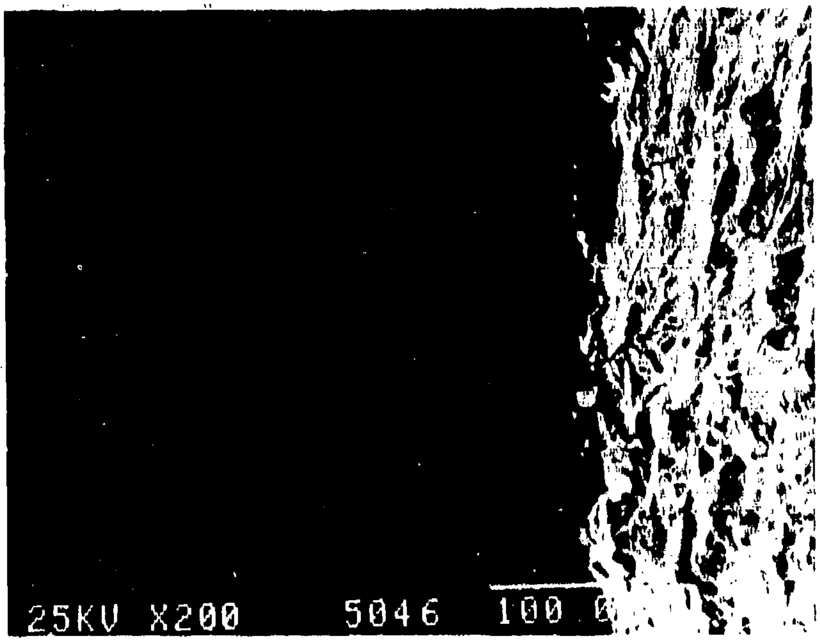


Figure 20. Oblique Fractograph of Specimen 17A; Left Side of Picture (Dark Surface) Is the Stripped Surface; Right Side (Light Surface) Is the Fracture Face. Note the fracture initiated on the stripped surface and the silica particle embedded in the initiation site. MAG: 200X

The second common feature detected by fractography was the texturing of the clad surface by the plastic bead paint removal. The left side of Figure 20 is an excellent example of this texturing. Since 7072 cladding is very soft it was either stripped off or smeared around the surface of the panel during plastic bead paint removal. This effect was confirmed by the metallographic cross sections described and depicted earlier in this report. In some cases, this texturing effect was very extensive and in other cases the effect was minimal. The most critical case for fatigue is when the texturing creates initiation sites, and for protection against corrosion the most critical case is when the blasting removes the cladding. It is important to understand the implications of damaging the cladding by plastic bead paint removal. The first implication is obvious: protection against corrosion offered by the cladding is reduced. Secondly, since the 7072 cladding is metallurgically bonded to the 7075 core, any damage to the cladding, such as pitting, scoring or cracking, can serve as crack initiation sites. Once these sites are introduced into the cladding, a crack can grow into the core material. Therefore, one could conclude that plastic bead paint removal creates surface defects in the soft 7072 cladding which serve as both crack initiation sites and coating defects.

Figures 19, 20, 21, 23, and 24 typify the features found on specimens whose early failures were attributed to plastic bead paint removal. The first obvious feature of the initiation site is on the plastic bead blasted side of the specimen; the initiation site is away from the edges and corners. The second obvious feature is the set of lines which radiate out from the initiation site into the core material. These lines can be traced back from the overload region to the initiation site no matter where the initiation site was located: corner, edge or surface. The third feature, which was particularly interesting and common to Specimen 17A only, is the particle embedded in the initiation site in Figures 19 and 20. X-ray analysis indicated that this particle was silica. It is believed that this particle was mixed in with the plastic beads when the plastic beads were manufactured or when the beads were recycled during the stripping operation. Another interesting feature on specimen 17A is the scored clad surface shown in Figure 21. Although it appears as if the 7075 core was exposed, it is believed that the cladding was scored by the stripping process.

Figure 22 shows a corner initiation site with a lip which was created during specimen machining. After these lips were detected in the test program, they

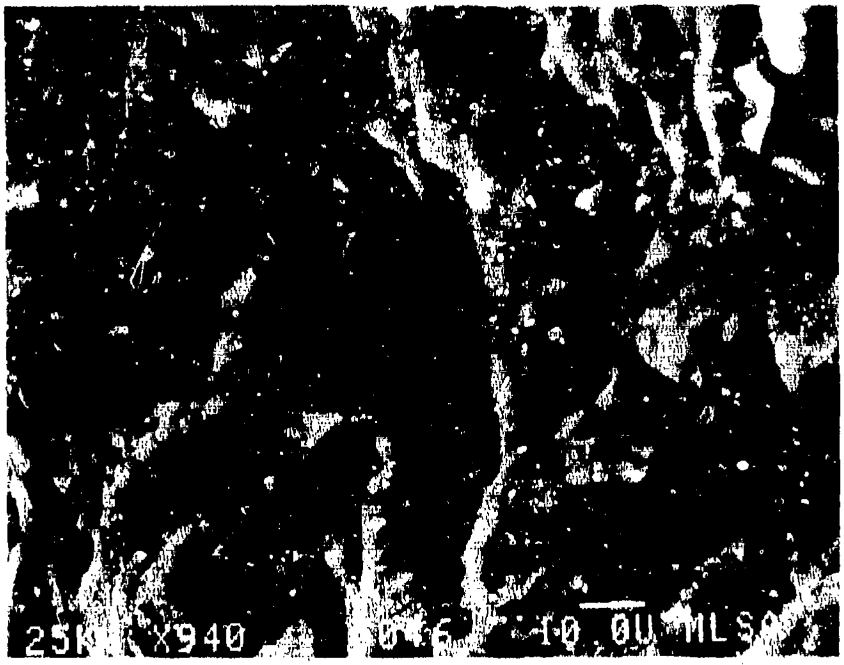


Figure 21. Close Up of Surface Depicted in Figure 20. Note the textured surface and the scoring which resulted from plastic bead blasting. MAG: 940X

Figure 22. Corner Fatigue Initiation Site on Specimen 50A. The fold was accidentally produced specimen machining and resulted in some premature failures. MAG: 200X

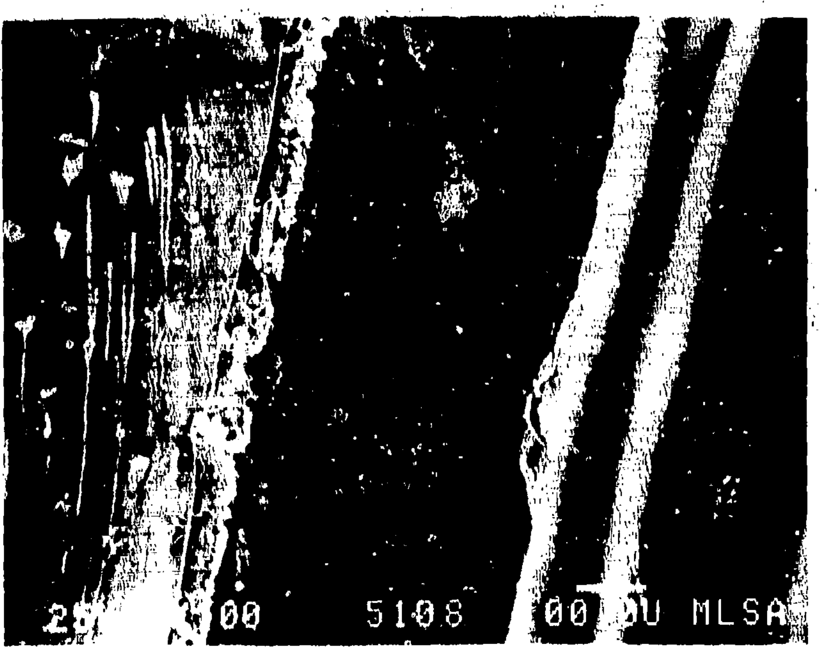
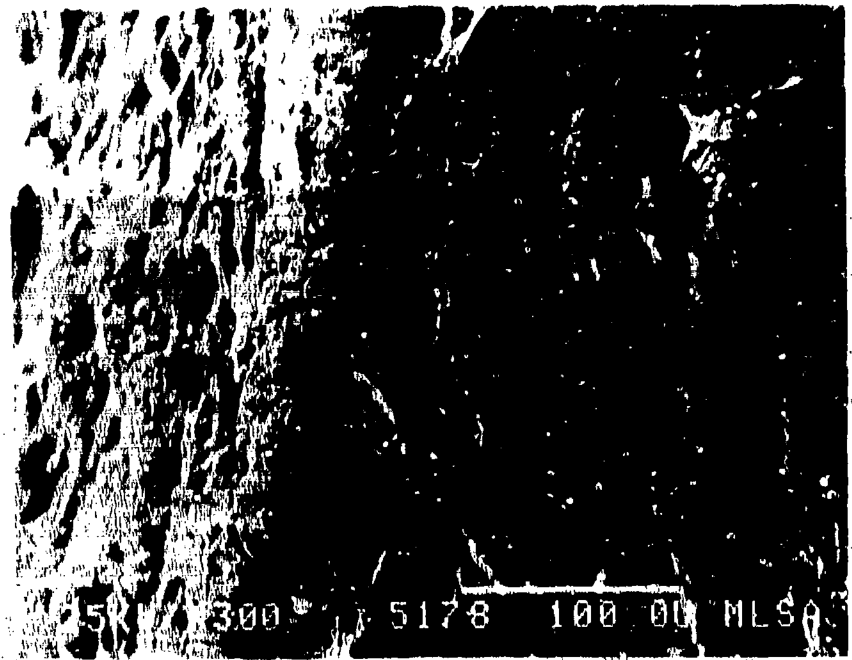
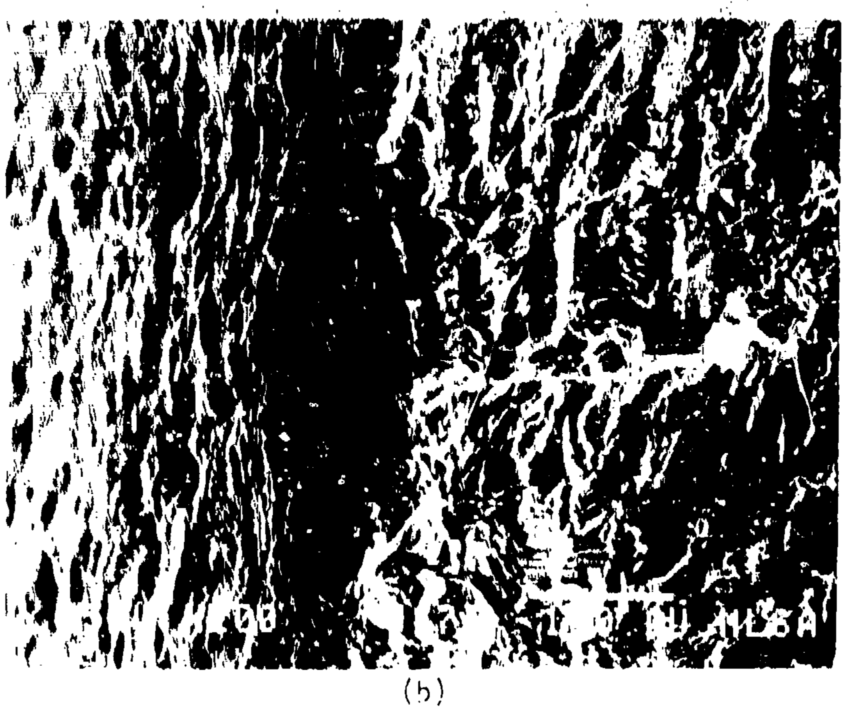


Figure 23. Initiation Site on Specimen 24B (Third Paint Removal at 38 psi). Note initiation site is near a surface defect. MAG: 100X



(a)



(b)

Figure 24. Fractographs Representative of the Fourth Paint Removal; (a) Specimen 67B; 38 psi; (b) Specimen 48B, 60 psi. Note the initiation site is a surface defect. MAG: (a) 300X, (b) 200X

were eliminated by rubbing emory paper up and down the edges of the fatigue specimens.

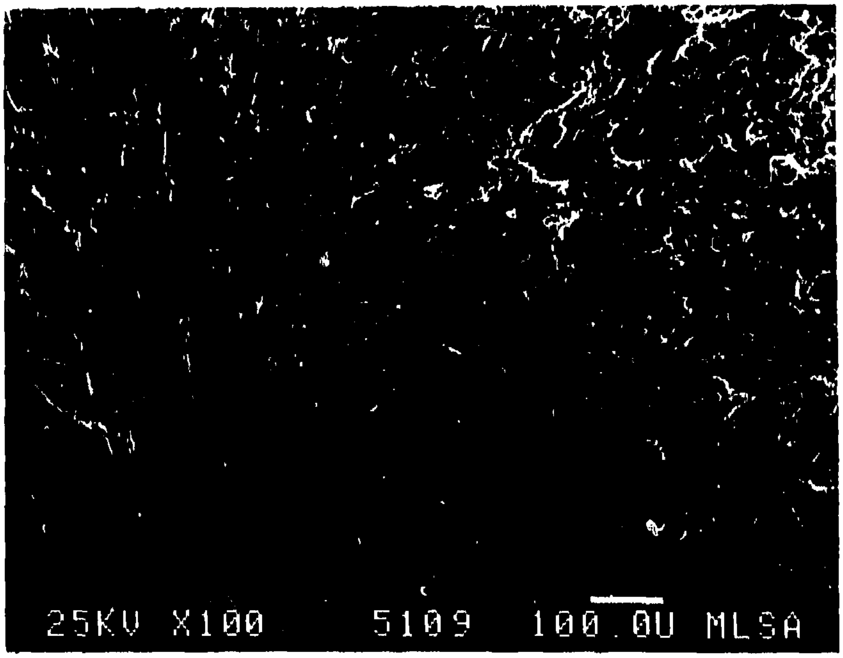
2. Alclad 7075-T6 Thin Skin Honeycomb Panel with Five Coats of Paint and One Stripping Operation

Fractographic analysis of these specimens revealed that they behaved similarly to the sequentially stripped panels described previously (Figure 25). The features included the same texturing of the cladding; the same initiation sites; the same fracture features; and the same effect due to the difference in nozzle pressure employed. This last feature is worth noting and discussing. At 38 psi nozzle pressure, the fatigue data indicates that there is more variability and earlier failures than at 60 psi nozzle pressure. It is speculated that two phenomenons are involved which explain the lower variability and longer lives of the 60 psi nozzle specimens. First, the specimens are subjected to plastic bead blasting for a shorter period of time since the paint is removed more quickly at 60 psi than at 38 psi. This shorter time reduces the number of surface defects that are introduced by plastic bead paint stripping. It is also speculated that the 60 psi nozzle pressures might cold work the surface, and in turn, offset the effects of introducing crack initiation sites, by retarding the crack propagation. Of course, more investigation is required to validate this theory.

3. Sulfuric Acid Anodized 7075-T6 Sheet (0.063 Inch Thick)

Figure 26 shows two fracture faces of sulfuric acid anodized 7075-T6 sheet which was subjected to plastic bead paint stripping. The cracks initiated at surface defects on the plastic bead blasted side of the specimens. Since the surface of the sulfuric anodized 7075-T6 is much harder than the cladding on the alclad 7075 sheet, it was less susceptible to damage by plastic beads; in turn, the less damage, the fewer the initiation sites, and the less effect on fatigue life. Although some surface defects were introduced during stripping, their effect was minimal since they were small with respect to the total thickness of the sheet material. In other words, as sheet thickness increases, the defects introduced by plastic bead blasting in materials should become less significant.

Figure 25. Fractograph of Specimen 36A (Five Coats of Paint/One Paint Removal). Initiation site is a surface defect. MAG: 320X



(a)

(b)

Figure 26. Typical Initiation Sites on the Sulfuric Acid Anodized 7075-T6. (a) Specimen SA-2 (b) Specimen SA-6. MAG: (a) 100X, (b) 200X

G. GRAPHITE/EPOXY MECHANICAL PROPERTIES (AS4/3501-6 MATERIAL)

1. Tensile and Flexure

The results from the tensile and four point flexure tests are given in Appendix B. These data are shown in Tables B2 to B8 and in comparative graphs presented in Figures B1 to B10. Based on information in Reference 2, a lognormal distribution was assumed for analyzing these data. Data distributions are shown in Figures B11 to B16, to illustrate that these various strength and modulus data have a reasonable fit to a lognormal distribution. This was done so that the "F" and "t" statistical tests (Reference 3) could be used to determine if the data groups have significantly different means or not. The post paint removal data groups were compared with their respective baseline data using these statistical tests. The statistical analysis results are shown in Table 6.

The maximum tensile strength reduction from the three quasi-isotropic laminates (Figures B1, B3, and B5) was 5.2%. These tensile strength data showed no significant difference from the baseline strength data when using the above statistical tests. Since tensile strength is a fiber dominated property, this indicates that no significant damage was done to the fibers during the paint removal process.

In the tensile modulus data (Figures B2, B4, and B6), the largest reductions in moduli were found in the $[90/0/\pm45/0/90]_s$ laminate. If matrix cracks are being introduced by the paint removal process, it would result in a reduction in the tensile modulus (Reference 4). Also the laminate having 90° plies on the outside would be expected to have the greatest reduction in stiffness. The fourth paint removal process using the 38 psi nozzle pressure produced a significantly lower mean modulus, 16.2% reduction, in this laminate, However, the other reductions of 11.5 to 12.1% were not found to be significant.

From Figure B7 (0° unidirectional laminate), the maximum reductions in the flexural strength occurred after four paint removals at 38 psi and 60 psi nozzle pressures. However, these 8.7% and 10.6% reductions were not statistically significant. These results also show that no significant damage was done to the fibers.

The reductions in the flexural strength for the 90° unidirectional and $[0/\pm45/0/90/0]_s$ laminates (Figures B8 and B9) were not consistent with regard to

TABLE 6

STATISTICAL ANALYSIS RESULTS ON COMPOSITE DATA

Mechanical Property	Fiber Orientation	Nozzle Pressure → / Nr. of Paint Removals →	38 PSI ONE	38 PSI TWO	38 PSI FOUR	60 PSI ONE	60 PSI TWO	60 PSI FOUR
Ultimate Tensile Strength	All three Quasi-isotropic	Results of F and t Statistical Tests: (1)	NO	NO	NO	NO	NO	NO
Tensile Modulus	[0/±45/0/90/0]s		NO	NO	NO	NO	NO	NO
	[90/0/±45/0/90]s		NO	NO	YES	NO	NO	NO
	[±45/0_2/90/0]s		NO	NO	NO	NO	NO	NO
Flexural Strength	0 deg. unidirectional		NO	NO	NO	NO	NO	NO
Flexural Strength	90 deg. unidirectional		NO	YES	NO	NO	YES	YES
Flexural Strength	[0/±45/0/90/0]s		YES	YES	NO	NO	YES	YES
Flexural Shear	[±45/0_2/90/0]s		YES	YES	YES	YES	YES	YES

(1) A "NO" indicates that no significant differences exist between the baseline data and the data obtained after paint removal using a 95% confidence level. A "YES" indicates that a significant difference did exist.

the number of paint removals using the 38 psi nozzle pressure. The data from both of these laminates showed significant reductions, 16.1% and 7.5%, after the second paint removal but not after the fourth paint removal. However, after the 60 psi nozzle pressure paint removal, both of the laminate's flexural strengths showed significant losses (10.7% to 14.2%) after both the second and fourth paint removals. These results and particularly those from the 90° unidirectional laminates are additional indications that matrix cracking did occur during the paint removal process.

The data shown in Figure B10 from the [±45/0/0/90/0]s laminate was obtained using the same four-point flexural test; however, the majority of the specimens failed by interlaminar shear and shear strength values were determined using Reference 1. Post test inspection of the failed specimens showed that the majority of these specimens failed by separating the laminate at the 90° ply at the 0/90 interface with the two adjacent 0° plies. In the majority of the specimens, this separation occurred at the 90° ply nearest the tensile stressed surface of the flexural specimen. However, several of the specimens from the fourth paint removal cycle contained ply separations at both of the 90° plies. Comparing with the baseline data, all of the shear strength means (arithmetic) after the paint removal cycles showed significant losses (20.5% to 28.7%). This is additional evidence of matrix cracking.

In summary, for this composite, AS4/3501-6 having no surface protection, statistically significant losses did occur in the matrix dominated mechanical properties, i.e., 90° unidirectional flexure strength and quasi-isotropic laminate flexure strength and flexural shear strength. No significant reductions occurred in the fiber dominated mechanical properties, i.e., ultimate tensile strength and 0° unidirectional flexural strength. These results provide evidence that matrix cracking has occurred as a result of the paint removal process but no significant damage to the fibers.

H. GRAPHITE/EPOXY FRACTOGRAPHIC STUDIES

SEM examinations were conducted on sections which were cut from the 12 ply 0° unidirectional four point flexure graphite/epoxy specimens after testing. The purpose of the examination was to determine if there was any damage to the material after plastic bead paint stripping. The examinations were conducted on the base material as well as on the test specimens which received either one, two, or four plastic bead paint removals. Both the 38 and 60 psi nozzle pressures were examined and the surfaces as well as the cross-sections were studied. The results of these investigations are detailed below.

1. Surface Examination Results

Examination of the surface of the baseline material revealed a gel coating on the top surface which was estimated to be approximately 0.0006 inches thick (Figure 27). (The pattern is a result of a peel ply placed on top of the gel coat.) After the first paint removal cycle, at both nozzle pressures, the gel coat was almost completely removed. Additionally, the fibers on the surface were broken in quite a few places and pieces of the broken fibers had fallen away. Figures 28 and 29 illustrate the surfaces for the 38 psi and 60 psi specimens after one round of plastic bead paint removal. The surfaces of the specimens receiving additional paint strip cycles revealed similar features except that with each paint and removal cycle there were even more broken and missing fibers on the surface. The only difference between the 38 psi and the 60 psi nozzle pressures appeared to be in the depth to which the surface fibers were damaged. On the 38 psi specimens, the damage most often consisted of broken single fibers whereas on the 60 psi specimens the damage contained more broken fiber bundles. The number of fiber layers which were completely removed was determined to be about 2-4 fibers in depth (even after four paint removals) or approximately 0.0006 to 0.0012 inches. Adding this to the 2-5 broken fiber layers means that about 4-9 fiber diameter layers were damaged. Because there are approximately 20 fiber diameters per ply, the surface damage to this 12 ply composite, even at 60 psi and after four paint removals, is less than one half of a ply or about 3-4% of the material in this case.

However, higher magnification of these surfaces revealed the following information. In addition to the broken fibers, there was also considerable fiber/matrix debonding and plastic working of the matrix on the surface (Figure 30). Additionally, the amount of plastic working in the matrix appeared to increase with the number of paint removal cycles. Compare Figure 30 at 60 psi after one cycle to Figure 31 at 60 psi after four cycles.

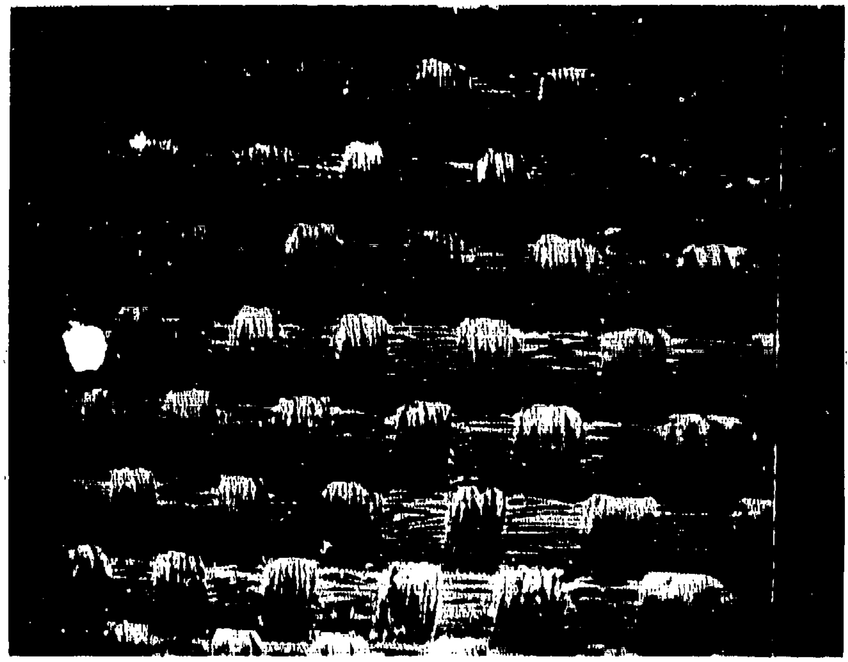


Figure 27. Surface Condition of the Graphite/Epoxy Base Material. MAG: 40X

Figure 28. Surface Condition of the Graphite/Epoxy Specimen After the First Paint Removal at 38 psi. MAG: 40X

Figure 29. Surface Condition of the Graphite/Epoxy Specimen After the First Paint Removal at 60 psi. MAG: 40X

Figure 30. Higher Magnification of the Graphite/Epoxy Specimen Surface After the First Paint Removal at 60 psi. MAG: 1000X

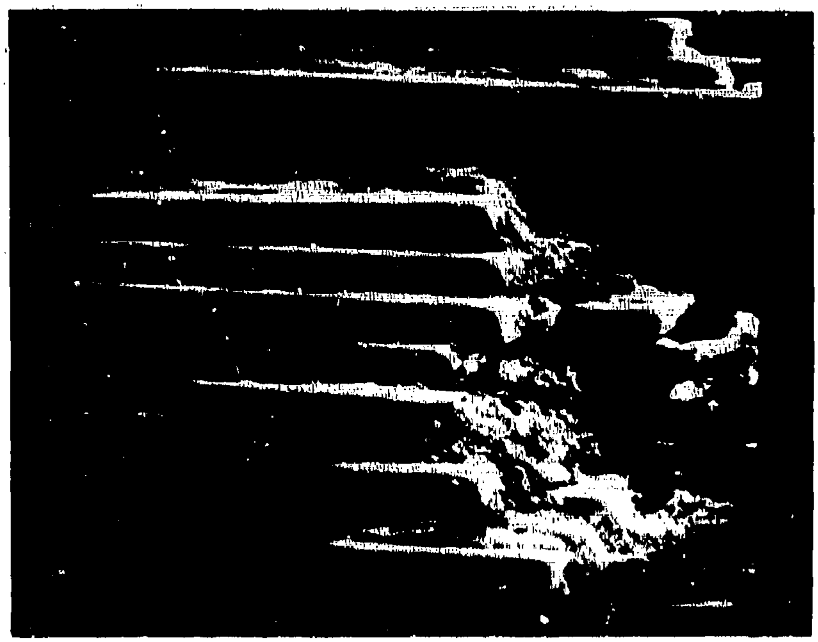


Figure 31. Surface Condition of the Graphite/Epoxy Specimen After the Fourth Paint Removal at 60 psi. MAG: 1000X

2. Cross-section Results

Cross-sections of the specimens revealed the following results. Again, the gel coating of the base material can be seen to have been removed after only one cycle at either nozzle pressure. Figures 32 to 35 depict the cross-sections of the baseline specimen and the paint removal specimens after one, two and four 38 psi paint removal cycles. These cross-sections indicate that the damage to the specimen consisted of more than that seen on the surface. These photographs indicate that additional damage was done to the material in the form of matrix cracking and fiber/matrix debonding below the surface. For the 38 psi nozzle pressure, the fiber/matrix debonding can be seen 3 to 5 fiber diameters deep after the first cycle, whereas after the second cycle it occurs approximately 3-8 fiber diameters down. After the fourth cycle, the debonding can be seen down approximately 4-10 fiber diameters in depth. Thus, it appears that the depth of the debonding damage somewhat increases as the number of paint strip cycles increases. In the 60 psi nozzle pressure samples the same type of damage is present and appears to go slightly deeper into the sample than for the lower pressures. For this case, debonding can be seen up to 3-6 fiber diameters deep after the first cycle and 5-12 fiber diameters deep after the second and fourth cycles. The matrix also appears to lose plasticity as the number of cycles increases as can be seen by comparing the ductility of the matrix of the base material (Figure 32) to the 38 psi paint stripped cross-sections (Figures 33 to 35). This difference can be seen throughout the specimen thickness and may be additional evidence that brittle matrix cracking has occurred as a result of the plastic bead paint removal operation.

3. 90° Flexural Test Specimen Results

One final examination was conducted on the 90° flexural specimens. This examination was conducted when the results of the 90° flexural test specimens started to show some significant decreases in properties after the second round of paint removal. SEM examination was then used to see if any reason for the decrease in the properties of these specimens could be noted. This study revealed the following information.

Figures 36 to 38 show the surfaces of the 90° flexural specimens for the baseline material and for the 60 psi nozzle pressure after the second and fourth

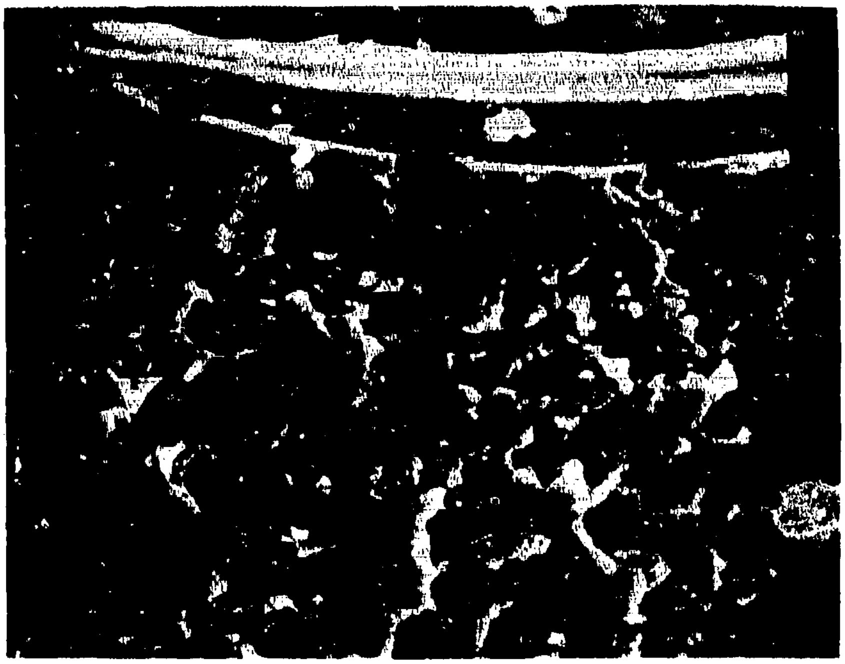


Figure 32. Cross Section of the Graphite/Epoxy Base Material. MAG: 1000X

Figure 33. Cross Section of the Graphite/Epoxy Specimen After the First Removal at 38 psi. MAG: 1000X

Figure 34. Cross Section of the Graphite/Epoxy Specimen After the Second Paint Removal at 38 psi. MAG: 1000X

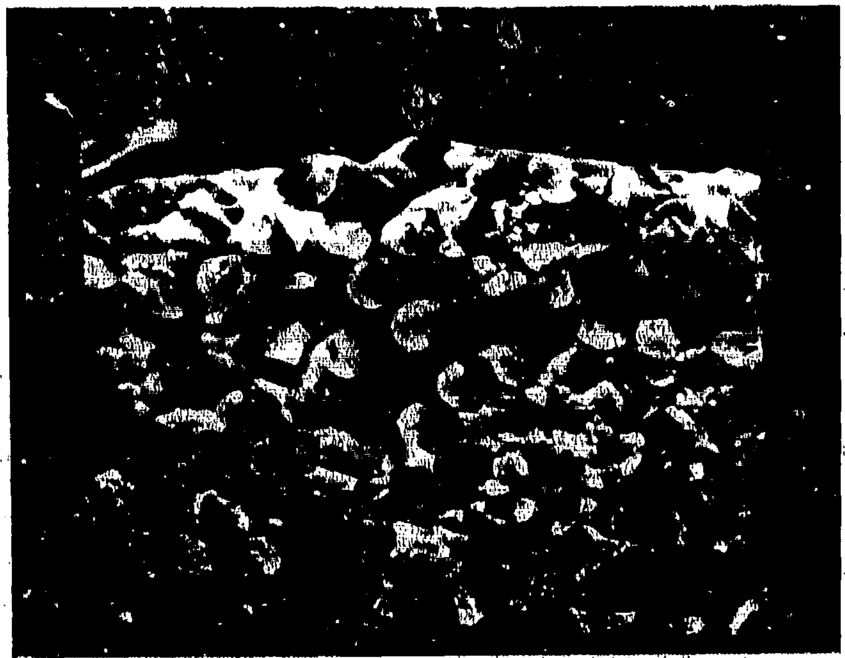


Figure 35. Cross Section of the Graphite/Epoxy Specimen After the Fourth Paint Removal at 38 psi. MAG: 1000X

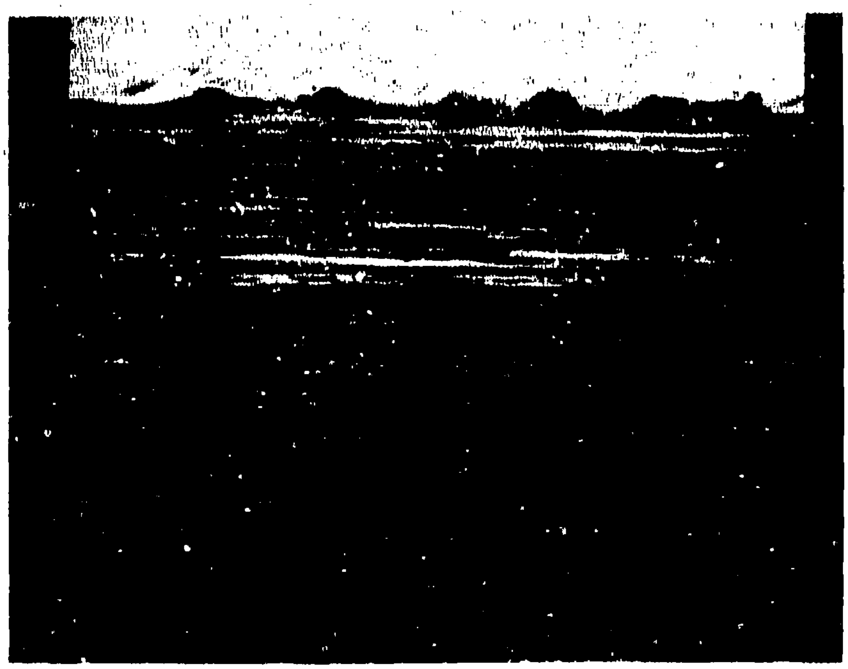


Figure 36. Fracture Surface of the 90° Flexural Specimen Base Material. MAG: 50X

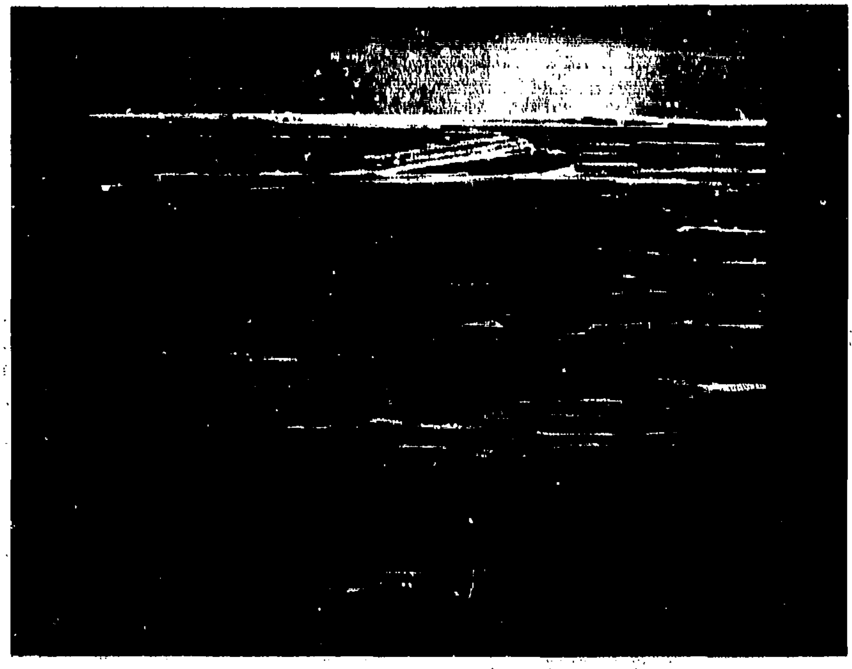


Figure 37. Fracture Surface of the 90° Flexural Specimen After the Second Paint Removal at 60 psi. MAG: 50X

Figure 38. Fracture Surface of the 90° Flexural Specimen After the Fourth Paint Removal at 60 psi. MAG: 50X

round of bead blasting. Since there were no significant losses in mechanical properties after the first paint removal, these specimens were not examined and the 38 psi specimens exhibited similar results to the 60 psi specimens and are not discussed here. The following surface features were noted. For the baseline material first, there were relatively few broken fibers; second, both the broken and the undamaged fibers appeared to be relatively intact with the matrix and third, the failure appeared to be predominantly a matrix type failure. For the plastic bead paint removal specimens, the following features were noted. First, there was a significant increase in the number of broken fibers on the surface, second, the matrix failed in a more brittle manner and third, the broken fibers were not intact with the matrix. Figures 39 and 40 further illustrate these differences. These features could indicate that the plastic bead paint removal operation caused matrix cracking. Precracking of the matrix in this manner would have caused brittle matrix failure and loss of matrix integrity. This would have resulted in significant fiber/matrix separation and loss of matrix below the main fracture surface upon testing. Additionally, this failure mode would have resulted in lower flexural strength values for the 90° unidirectional specimens.

4. Summary

In summary, there is significant damage to the graphite/epoxy composite materials from the plastic bead paint stripping operation under the conditions of this investigation. This damage consists of (1) the removal of the gel coating, (2) the removal of some fiber layers and subsequent breakage of many of the remaining surface fibers (3) some fiber/matrix debonding and cold working of the matrix on the surface layers, and (4) some matrix cracking and fiber/matrix debonding up to 12 fiber diameters in depth at the worst case studied. Furthermore, the difference in appearance of the cross-sections and the failure mode of the 90° flexural indicates that there is matrix cracking even after as few as two plastic bead paint removal cycles.

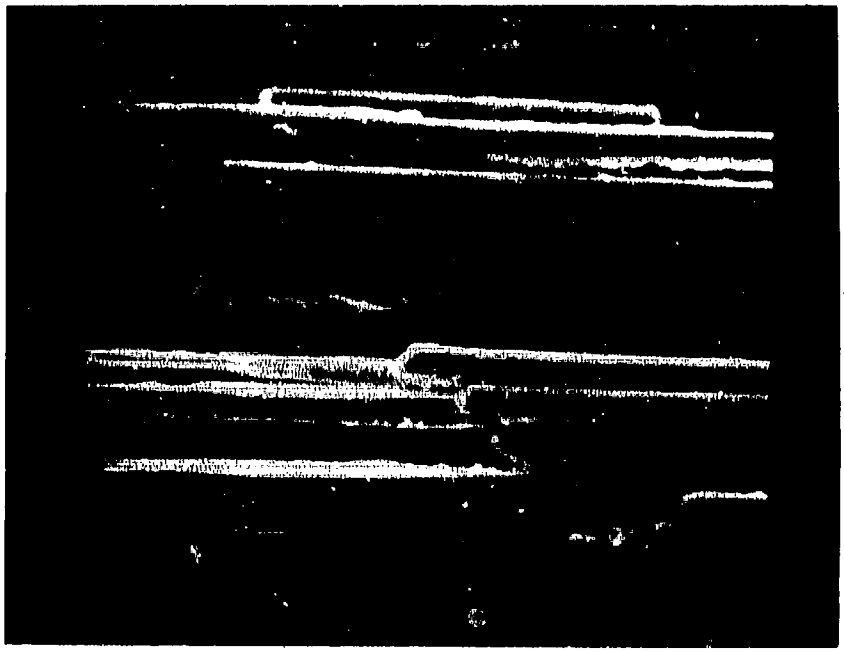


Figure 39. Further Magnification of the 90° Flexural Specimen Base Material. MAG: 500X

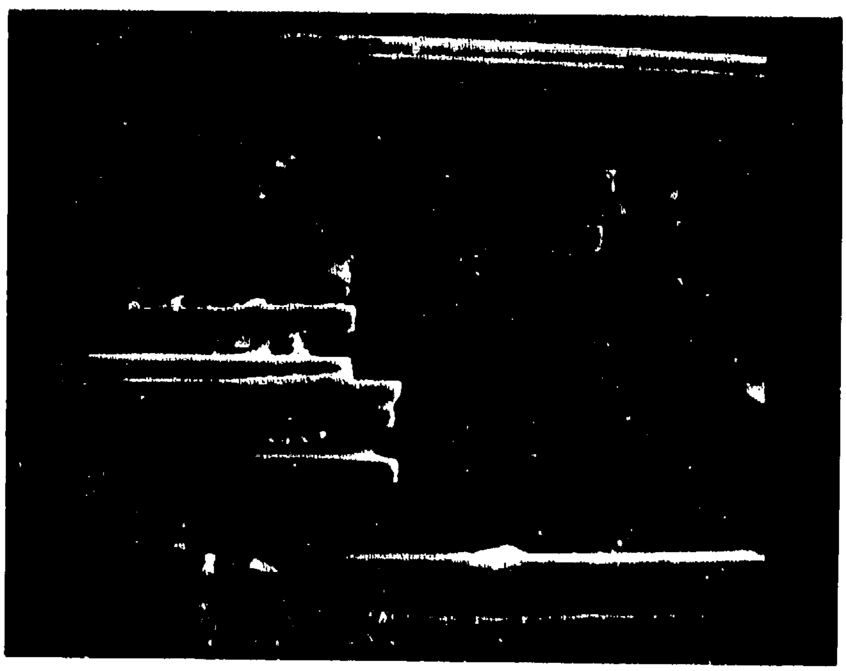


Figure 40. Further Magnification of the 90° Flexural Specimen After the Fourth Paint Removal at 60 psi. MAG: 500X

SECTION IV

GUIDELINES FOR EVALUATING THE EFFECTS OF PLASTIC BEAD PAINT REMOVAL ON METALLIC MATERIALS

A. DISCUSSION

Since plastic bead blasting for paint removal from aerospace systems is being considered as a possible process for replacement of chemical strippers, the use of such a process on an aerospace system immediately raises a major concern of the effects on the mechanical and physical properties of structural materials. Other concerns are effects on bearings and sliding parts and contamination of electronic compartments and components.

In any abrasive cleaning operation (paint removal) damage on some surfaces in terms of substrate removal, surface roughness, warpage, etc., is unavoidable. Implied in this statement is the acceptance of some damage inasmuch as it would be impossible to develop an effective process that would not cause some changes to the base material. The task, then, is to define what is acceptable in terms of changes to materials' physical and mechanical properties. The following table and accompanying evaluation procedures were prepared to provide some guidance for evaluating the effects of plastic beads on metallic structure.

The first step in the procedure is to determine whether or not the part to be exposed to the paint removal process is fracture critical. Those that are designed to damage tolerance criteria should receive more scrutiny than parts which are designed for durability and that are cosmetic or serve only as aerodynamic fairings. This is reflected in Table 7 and the accompanying test procedure by the increased number of properties to be evaluated. The evaluation process could ultimately lead to a decision to perform tests. However, the decision to test or not to test must be based on good engineering assessment. For instance, if the same alloy and heat treatment was previously evaluated in a test program and minimum changes in properties were found, it would probably be acceptable to release that part for plastic bead paint removal. Another part may be made of material that has properties similar to a previously tested alloy. In such a case one might want to conduct a metallographic evaluation to assess if damage is similar to, better, or

TABLE 7

METALLIC MATERIALS MINIMUM TEST EVALUATIONS

Plastic Bead Paint Stripping Process Evaluation

FRACTURE CRITICAL PARTS	METALLO-GRAPHY	SURFACE ROUGHNESS	FATIGUE TESTS	CRACK GROWTH RATE TESTS	SURFACE CONDUCTIVITY	FRACTO-GRAPHY
Al-Clad	X	X	X	X		
Al - Bare, Anodized	X	X	X	X	X	X
Ti	X	X	X	X		X
OTHER PARTS						
Al-Clad	X	X				
Al - Bare, Anodized	X	X				
Ti	X	X				

Distortion to be measured on thin materials (less than 0.020) worse than that in the already cleared alloy. A material that has not been evaluated should receive applicable testing.

B. METALLOGRAPHY

1. Scope

1.1 This procedure contains the general requirements for evaluating metallographically the effects of Plastic Bead Paint Removal (PBPR) on metallic structures and gives general direction only. Specific details and techniques are well documented in existing industry standards.

2. Applicable Documents

ASTM E 7	Metallography, Definitions of terms relating to.
ASTM E 2	Methods for Preparation of Micrographs of Metals and Alloys (Including Recommended Practice for Photography as Applied to Metallography).
ASTM E 3	Methods for Preparation of Metallographic Specimens.
ASTM E 340	Methods for Macroetching Metals and Alloys.
ASTM E 407	Methods for Microetching Metals and Alloys.

3. Definitions

Definitions will be in accordance with the documents listed in Section 2.

4. General Requirements

4.1 Discussion. Metallography allows material evaluators to relate the constitution and structure of metals and metal alloys to their properties. When properly employed, metallography can prove useful in evaluating the effects of plastic bead paint removal on metallic structures. In particular, metallography can reveal the 2-D surface features created by PBPR; scanning electron microscopy can reveal the 3-D features. By using these techniques, the effects of plastic bead paint removal can be assessed. Since the details of metallography are already well documented, the evaluator is directed to existing standards.

4.2 Requirements. The general requirements are listed to give guidance to the evaluator, but in no way dictate the absolute method for evaluating PBPR with metallography.

4.2.1 Specimen Selection. Accurate selection of the metallographic specimen is probably the most important step in evaluating the effects of PBPR metallographically. The specimen must represent the material and process being studied. Generally, the specimen selected is a transverse cross-section which will best reveal variations in structure from center to surface; thickness and structure of protective coatings; depth and type of surface anomalies; and any other feature created by PBPR. The specimen size shall be amenable to mounting and preparation techniques.

4.2.2 Specimen Sectioning. Specimens shall be sectioned such that the structure to be studied is not damaged during sectioning. Lubricants and cooling media typically prevent microstructural or physical damage from occurring during sectioning.

4.2.3 Specimen Mounting. Cross-sections shall be carefully mounted to reveal as much detail as possible. Soft alloy surfaces can be plated before mounting or hard mounting material can be employed to prevent smearing of the edges during subsequent grinding and polishing operations.

4.2.4 Grinding and Polishing Operations. These operations are well standardized and should be adhered to.

4.2.5 Etching Operations. These operations are also well documented and can be matched to the material under study.

4.2.6 Specimen Evaluation. Light or scanning electron microscopy can be used for evaluating the effects of PBPR, particularly the surface effects. Photomicrographs should be taken of areas which are typical and which best illustrate the effects of PBPR.

5. Notes

5.1 To accurately characterize and evaluate the effects of PBPR metallographically, several specimens must be analyzed.

5.2 Metallography should be used in conjunction with other techniques to evaluate the effects of PBPR. Decisions should <u>not</u> be based on only a few metallographic specimens.

C. SURFACE ROUGHNESS MEASUREMENTS

Surface roughness of exterior aircraft structure caused by sanding, abrasive blasting using various types of abrasive media or other means of mechanically abrading the surface can result in several unsatisfactory performance phenomena. Some of these include increased aerodynamic drag, fatigue crack originators, increased fatigue crack growth rates, and potential increased corrosion rates. All of the above potential effects on aircraft structure must be assessed for each aircraft system in terms of total average roughness and whether the roughness is on critical or noncritical structure.

There are several instruments commercially available for measuring surface roughness including mechanical and optical (laser) devices. The procedure for measuring surface roughness will be dependent on the particular instrument being used.

D. FATIGUE

1. Scope

1.1 This section contains the general requirements for evaluating the effects of Plastic Bead Paint Removal on the fatigue properties of metallic materials. This section gives direction only. Specific procedures and techniques are well documented in existing industry standards.

2. Applicable Documents

2.1 Definitions of Terms Relating to:

ASTM E 206	Fatigue Testing and the Statistical Analysis of Fatigue Data

2.2 Method/Practice:

ASTM E 466	Conducting Constant Amplitude Axial Fatigue Tests of Metallic Materials
ASTM E 468	Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials
ASTM E 467	Verification of Constant Amplitude Dynamic Loads in an Axial Load Fatigue Testing Machine
ASTM E 739	Statistical Analysis of Linear or Linearized Stress - Life (S-N) and Strain Life (E-N) Fatigue Data
MIL-HDBK-5C	Chapter 9, Section 9.6, Subsection 9.6.2, Tests of Significance

3. Definitions

3.1 Definitions will be in accordance with the documents listed in Section 2.

4. General Requirements

4.1 Discussion

Fatigue is a failure mode that is composed of two stages; crack nucleation and crack propagation. Crack nucleation usually occurs at some imperfections or discontinuities in a material such as inclusions, machining scratches, fastener holes, etc. Crack propagation in normal material is dependent on the average properties of a material with localized imperfections playing a secondary role in the process. (Further discussion of fatigue crack propagation is contained under the heading of Fatigue Crack Growth Rate.) From the foregoing it can be seen that plastic bead cleaning will potentially have a significant effect on fatigue data inasmuch as crack nucleation sites may be introduced on the surface of the material by the cleaning process. Of all mechanical properties fatigue will potentially be affected the most. If it is determined that fatigue tests must be run on a material, a program that will result in meaningful data must be conducted.

4.2 Requirements

The general requirements are listed to give guidance to the evaluator, but in no way dictate the absolute method for evaluating the effects of plastic bead paint removal on fatigue properties.

4.2.1 Planning

It must be determined if a fatigue data base exists for the material, heat treat, and surface condition under consideration. If a fatigue data base does not exist on the material, it is recommended that a S-N (stress-life) curve as shown in ASTM Standard Practice E 468 be developed using 10 to 15 valid fatigue test data. If fatigue data is available or after generating the data, it is recommended that baseline specimens be tested at two stress levels, i.e., one stress that will produce fatigue life at about 100,000 cycles and the other stress that will produce a fatigue life at about 1,000,000 cycles. At each of these stress levels five valid fatigue tests are to be performed on the base material. After subjecting blanks of the same material with a painted surface to the paint removal process, ten valid fatigue tests are to be conducted, i.e., five tests at each of the above selected stress levels.

4.2.2 Specimen Design and Preparation

For sheet material the test specimens are to have a rectangular cross section having a minimum width of one inch in the reduced test section. The length of the uniform test section, between the belding fillets, should be a minimum of two inches. An example of a test specimen is shown in the attached drawing which was used to test 0.063 inch-thick 7075-T6. Aluminum grip tabs were bonded on the ends of the specimens using FM-300 epoxy film adhesive. Specimen preparation must be done with great care to avoid undercutting at the fillets, introducing residual stresses, or having stress risers along the machined edges. In the final stages of machining, material must be removed in small amounts until 0.005 inch of excess material remains on each machined edge. The next 0.004 inch of material should be removed at a rate of 0.001 inch per machining pass. The final 0.001 inch of material on each edge must be removed by polishing longitudinally to the length of the specimen. All specimens are to be inspected using 20X or greater magnification. All transverse marks, cracks, or excess material, such as burrs along the machined edges, shall be removed or the specimen is to be discarded.

4.2.3 Testing

The fatigue tests are to be conducted at room temperature in accordance with ASTM Standard Practice E466 and preferably using electrohydraulic servo-controlled testing machines. For material in sheet form, the tests should be performed using axial tension-tension type of loading. It is suggested that the following stress ratios (min stress/max stress = R) be used:

(1) For sheet material having a thickness less than 0.050 inch, use a stress ratio (R) of 0.3.

(2) For sheet material with a thickness greater than 0.050 inch, use a stress ratio (R) of 0.1. The test frequency should be between 10Hz to 25Hz. All of the fractured specimens are to be analyzed using fractography to determine if each test is valid, i.e., failure occurring within the specimen and not at a machining burr along the machined edge of the specimen.

4.2.4 Test Results and Analysis

The fatigue data shall be reported as given in ASTM Standard Practice E468. If five valid test data are available at a single stress level for both baseline and the paint removal conditions, then a statistical t-test may be conducted to test for a significant difference between the two sample means. Logarithms of the specimen lives are to be used since it is common practice to assume that the logarithms of the fatigue lives belong to a normal distribution. See Subsection 9.6.2 in MIL-HDBK-5C.

If the S-N fatigue data from the base material can be described by a linear model, 95% confidence bands for the S-N curve can be obtained. See ASTM E 739. The data, obtained from the specimens that were subjected to the paint removal process, can then be compared to these confidence bands.

E. FATIGUE CRACK GROWTH RATES

1. Scope

Contained herein are generalized concepts and procedures for evaluating the effects of Plastic Bead Paint Removal (PBPR) on the fatigue crack growth rates of metallic structural elements. Each part must be evaluated in terms of the particular loading environment to which it is exposed and its interaction with other structural components.

2. Applicable Documents

ASTM E 647	Standard Test Method for Constant-Load-Amplitude Fatigue Crack Growth Rate Above 10^{-8} m/cycle. NOTE: This method is going to be retitled Standard Test Method for Measurements of Fatigue Crack Growth Rates
AFWAL-TR-82-3073	USAF Damage Tolerance Design Handbook: Guidelines for the Analysis and Design of Damage Tolerant Aircraft Structures
MCIC-HB-01R	Damage Tolerance Design Handbook; A Compilation of Fracture and Crack Growth Data for High Strength Alloys

3. Definitions

Definitions will be in accordance with the documents listed in Section 2.

4. General Requirements

4.1 Discussion. Fatigue crack growth rate (FCGR) information obtained from tests on specimens is used to predict the growth of cracks in structures. A change in the growth rate in specimens will translate to a similar change in the growth rate of a crack in a component. The growth of a fatigue crack at any given time is governed primarily by the material directly ahead of the progressing crack. To consider the possible effects of plastic bead cleaning on crack growth a starting point is to view the material near the crack tip. It can easily be visualized that unless a large portion of this material is altered in its basic properties the FCGR will not change.

4.2 Requirements. The general requirements are listed to give guidance to the evaluator. Specifics of testing are given in the applicable documents. Interpretation of results must take into consideration that FCGR, like fatigue, has variability.

4.2.1 Test Design. To accurately assess any effects of PBPR on FCGR, tests on virgin and PBPR panels must be run in a side by side comparison. All specimens must be removed from one piece of material and tested to one set of parameters (stress ratio, frequency, environment).

4.2.2 Data Requirements. Sufficient raw data (crack length and cycle count) must be obtained to develop an accurate description of the fatigue crack growth rate (da/dN) over at least one decade on the growth rate axis. Larger portions of the curve are desirable. There must be at least ten points within a decade. For ease of data generation the lowest growth rate should not be lower than 10^{-7} in/cycle and for accuracy the fastest growth rate should not be higher than 10^{-4} in/cycle.

4.3 Data Interpretation. Assessment of the effects can best be accomplished by fitting a line or curve to the da/dN vs k data. Differences in results should be obtained from the fitted curves.

F. SURFACE ELECTRICAL CONDUCTIVITY

1. Scope

1.1 This procedure provides the general requirements to determine if anodize coatings have been removed from aluminum alloys using the surface electrical conductivity technique.

2. Applicable Documents

None

3. Definitions

None

4. General Requirements

4.1 Discussion. Anodize coatings, chromic and sulfuric, are applied to aircraft aluminum structure for increased long term protection against corrosion. Properly applied undamaged anodize coatings are electrically nonconductive. Therefore, the procedure for determining if an anodize coating has been damaged during refinishing processes is to use a volt/ohm meter to determine if electrical conductivity is present in areas of the anodized structure. This procedure assumes that the anodize coating was undamaged prior to paint removal from the aircraft either by sanding, plastic bead blasting or with chemical strippers.

4.2 The test procedure is as follows:

a. Using 300 grit sand paper, lightly remove a small area, not to exceed one square inch of the anodize coating.

b. Position both electrodes of the volt/ohm meter in the sanded area to ensure electrical conductivity.

c. Maintain contact of the positive electrode with the sanded area and slowly move the negative electrode over the area to be inspected for damaged anodize coating.

d. Any deflection of the volt/ohm meter indicator shows areas with the absence of the anodize coating.

5. Notes

None

G. FRACTOGRAPHY

1. Scope

1.1 This brief contains the general requirements for evaluating the effects of Plastic Bead Paint Removal by using fractographic evaluation techniques. The brief gives direction only; specific details, procedures and techniques are well documented in existing literature.

2. Applicable Documents

Publications

MCIC-HB-06 SEM/TEM Fractography Handbook

MCIC-HB-08 Electron Fractography Handbook

3. Definitions

3.1 Definitions will be in accordance with the documents listed in Section 2.

4. General Requirements

4.1 Discussion. Fractography (light or electron) is a valuable technique for determining whether or not Plastic Bead Paint Removal (PBPR) is the cause of failure of metallic structures subjected to PBPR. Fractography, in conjunction with metallography and other evaluation techniques, can assist in assessing the effects of PBPR. Since the details of fractography are already well documented, the materials evaluator is directed to that documentation for specific procedures and techniques.

4.2 Requirements. The general requirements are listed to give guidance to the materials evaluator and in no way dictate the absolute method for evaluating the effects of plastic bead paint removal with fractography.

4.2.1 Specimen Selection. Accurate specimen selection is necessary for correlating the effects of plastic bead paint removal to the properties of the material subjected to PBPR. In selecting the specimen, the critical feature is the crack initiation site. Once the initiation site is located, it can be determined if PBPR was responsible. Therefore, it is critical that the specimen selected include initiation sites on the plastic beaded surface.

4.2.2 Specimen Selection and Preparation. Once the specimen for study is selected, it should be carefully sectioned so as not to damage the surfaces in question. Techniques for sectioning and preparing fractrographic specimens are well documented and should be referred to.

4.2.3 Specimen Evaluation. The critical features sought after using fractography include fatigue failure initiation sites, protective coating integrity, and surface finishes. By using a variety of techniques, the evaluator can determine if PBPR degraded or upgraded the beaded material. Although the evaluation is subject to interpretation, several observations are required to conclusively determine the effects of PBPR on material properties using fractography.

5. Notes

5.1 Like metallography, fractography involves exceptional skill and technique. If used properly, the effects of plastic bead paint removal can be assessed accurately.

SECTION V

CONCLUSIONS

A. METALLIC STRUCTURE

1. The plastic bead blasting process for paint removal caused warpage in unsupported thin skin aluminum material that was blasted at either 38 psi or 60 psi nozzle pressure.

2. The plastic bead blasting process for paint removal did not effect the adhesive bond strength of aluminum honeycomb structure and thin skin metal to metal bonded structure that was blasted at either 38 psi or 60 psi nozzle pressures.

3. The surface roughness values in microinches resulting from plastic bead blasting 0.016 inch thick alclad 7075-T6 aluminum showed the following.

a. High surface roughness after the first plastic bead blast paint removal on panels blasted at either 38 psi nozzle pressure or 60 psi nozzle pressure.

b. The surface roughness values decreased after each of the four consecutive plastic bead blastings on test specimens blasted at either 38 psi or 60 psi nozzle pressure.

c. The application of the standard Air Force exterior aircraft finish to the plastic bead blasted surfaces decreased the surface roughness values to acceptable levels.

4. The alclad thickness on alclad aluminum alloys is 6.4% of the total material thickness. Consequently, surface roughness values will vary greatly depending on the thickness of the alclad aluminum alloy subjected to the plastic bead blast paint removal process. Therefore, the effects of surface roughness will have to be assessed for each weapon system based on final surface roughness after paint application and the total effected critical surface area.

5. The plastic bead blasting process for paint stripping removed the alclad coating from aluminum structure that was blasted at either 38 psi or 60 psi nozzle pressure.

6. The plastic bead blasting process for paint removal removes both chromic acid and sulfuric acid anodize coatings from both alclad aluminum and bare aluminum at either 38 psi or 60 psi nozzle pressure.

7. The fatigue properties for thin skin alclad 7075-T6 aluminum honeycomb materials which were subjected to four consecutive plastic bead paint removal cycles at either 38 psi nozzle pressure or 60 psi nozzle pressure showed the following:

a. Thin skin aluminum material blasted at 38 psi nozzle pressure. The accumulative percentage of the total tests falling below the lower 95% confidence curve increases with the number of paint removals.

b. Thin skin aluminum material blasted at 60 psi nozzle pressure. The accumulative percentage of total tests falling below the 95% confidence curve decreases with the number of paint removals which indicates that the higher blast pressure is less damaging in fatigue.

8. The fatigue properties for 0.063 inch thick sulfuric acid anodized 7075-T6 unclad aluminum materials which was plastic bead blasted one time for paint removal at either 38 psi or 60 psi nozzle pressure showed the following.

a. Unclad anodized aluminum sheet blasted at 38 psi nozzle pressure. All of the specimens failed above the lower bound curve to the baseline data. However, all the fatigue cracks in these specimens initiated on the side of the panel that had been blasted with the plastic beads for paint removal.

b. Unclad anodized aluminum sheet blasted at 60 psi nozzle pressure. All of the specimens failed above the lower bound curve to the baseline data. The majority of the fatigue cracks in these specimens did not originate on the side of the panel that had been blasted with the plastic beads for paint removal. These specimens also had longer fatigue lives than those blasted at 38 psi nozzle pressure which is in agreement with the fatigue results found for the thin skin aluminum materials. This is further supporting data that the higher blast pressure is less damaging in fatigue.

9. An embedded particle which was shown by x-ray analysis to be silica (sand) was found by metallographic examination to be at the crack initiation site in one of the thin skin aluminum fatigue specimens. This foreign particle was obviously mixed in with the plastic beads and impacted the test specimen during the paint removal operation. Equipment will have to be installed to remove foreign particulate matter from the plastic bead blasting process in order to eliminate potential crack initiation sites in aircraft structure.

B. GRAPHITE/EPOXY COMPOSITE STRUCTURE

1. The gel coat of the graphite/epoxy specimens was removed by both the 38 psi nozzle blast pressure and the 60 psi nozzle blast pressure after just one paint removal cycle.

2. Statistically significant losses in the matrix dominated physical properties (flexural strength and flexural shear strength) occurred for the composite material that was plastic bead blasted at 38 psi nozzle pressure and at 60 psi nozzle pressure. These mechanical property losses were attributed to matrix cracking.

3. No statistically significant fiber dominated (ultimate tensile strength and 0° unidirectional flexural strength) mechanical property losses occurred for this composite material that was plastic bead blasted at 38 psi nozzle pressure and at 60 psi nozzle pressure. With the exception of minor fiber damage in the surface ply, no significant fiber damage resulted from the plastic bead blast paint removal process.

C. PLASTIC BEAD BLAST PAINT REMOVAL PROCESS CHARACTERIZATION

1. No characterization of the plastic bead blast paint removal process was made in the following areas.

a. Blast nozzle angle of attack relative to the surface being plastic bead blasted for paint removal versus paint removal rates versus damage to the structural material.

b. Blast nozzle stand-off distance from the surface being plastic bead blasted for paint removal versus paint removal rates versus damage to the structural material.

c. Plastic bead size and hardness versus paint removal rate versus damage to the structural material.

d. Blast nozzle pressures other than 38 psi and 60 psi.

SECTION VI

RECOMMENDATIONS

A. METALLIC STRUCTURE

1. An Alman strip intensity study of plastic bead blasting (peening) on aluminum thin skin structure should be accomplished.

2. Any aircraft structure determined to be fracture critical should, as a minimum, be evaluated in accordance with the guidelines in Section IV of this report prior to removing paint from that structure by the plastic bead blast process.

3. A test program should be accomplished to determine the optimum nozzle angle of attack relative to the surface being blasted, the optimum nozzle stand-off distance from the surface being blasted, the optimum nozzle blast pressure, and the optimum plastic bead size and hardness in order to define a safe, efficient, and damage free window of operation for plastic bead blast paint stripping.

4. A test program should be accomplished to determine the effects on long term protection against corrosion of alclad, ion vapor deposited aluminum, and cadmium coated surfaces which have been plastic bead blasted for paint removal.

5. Rigid process and quality control measurements are required for the plastic bead paint removal process to eliminate foreign object damage (FOD) of aircraft structure.

B. EPOXY/GRAPHITE COMPOSITE STRUCTURE

1. Significant losses occurred in matrix dominated properties as a result of plastic bead paint removal from graphite/epoxy composite. Consequently, paint should not be removed from graphite/epoxy composite structure using the plastic bead blast process.

2. Means of protecting graphite/epoxy composite matrix cracking from the plastic bead blast paint removal process such as protective outer film plies or chemically softening the paint coatings prior to plastic bead blasting should be evaluated.

REFERENCES

1. C. E. Browning, F. Abrams, and J. M. Whitney, "A Four-Point Shear Test for Graphite/Epoxy Composites," Composite Materials: Quality Assurance and Processing, ASTM STP 797, American Society for Testing and Materials, 1982.

2. J. M. Whitney, "Use of the Lognormal Distribution for Characterizing Composite Materials," Composite Materials: Testing and Design (Sixth Conference), ASTM STP 787, I. M. Daniel, Ed., American Society for Testing and Materials, 1982.

3. MIL-HDBK-5-C, Chapter 9, "Guidelines for the Presentation of Data," 15 September 1976.

4. S. L. Ogin, P. A. Smith, and P. W. R. Beaumont, "Matrix Cracking and Stiffness Reduction During the Fatigue of a (0/90)s GFRP Laminate," Composites Science and Technology, 22 (1985).

APPENDIX A

FATIGUE DATA

All of the fatigue data generated during this program are shown in this section. These data are shown in both tabular and graphical form.

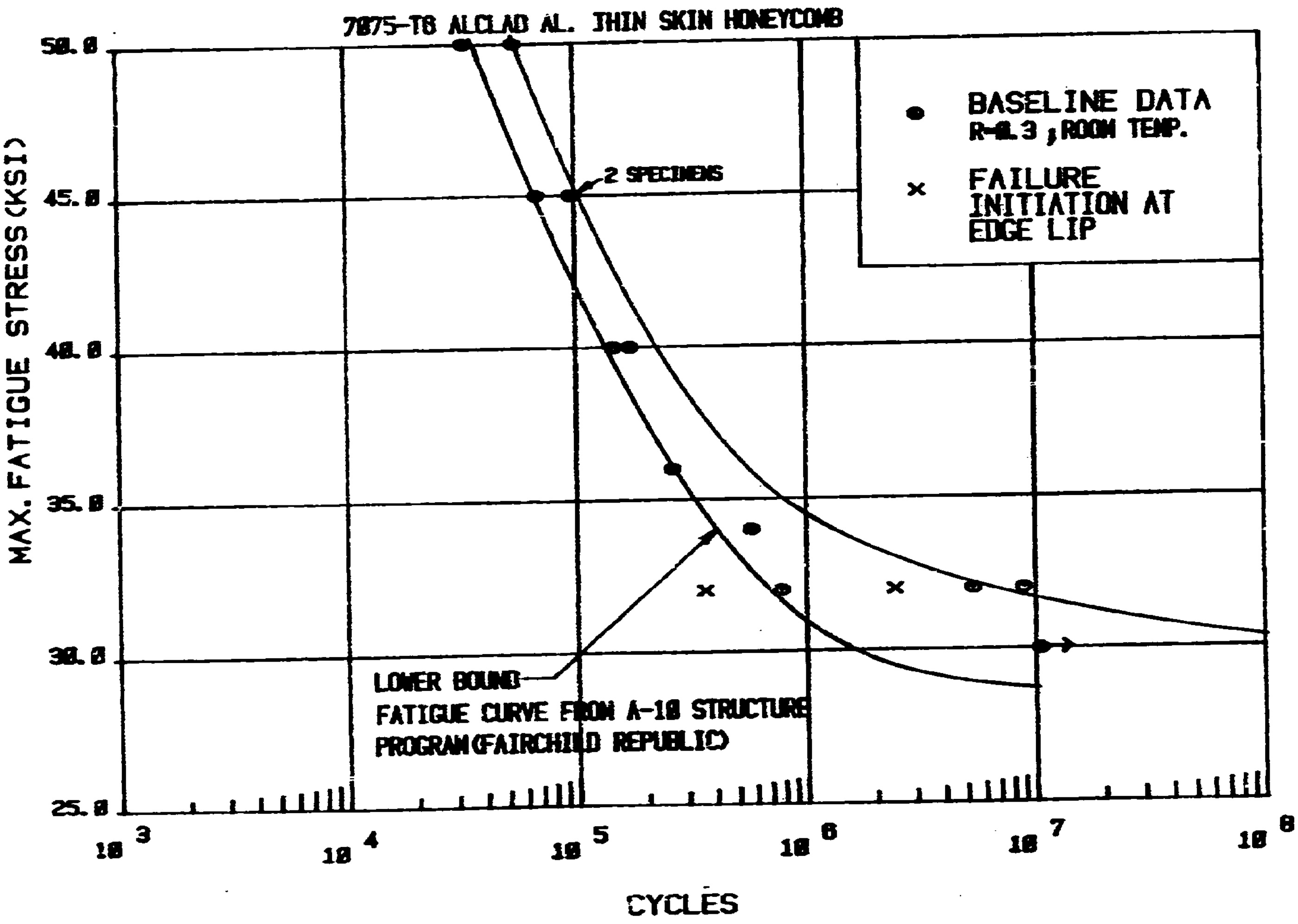


Figure A1. Baseline Fatigue Results on 7075-T6 Alclad Al Thin Skin Honeycomb

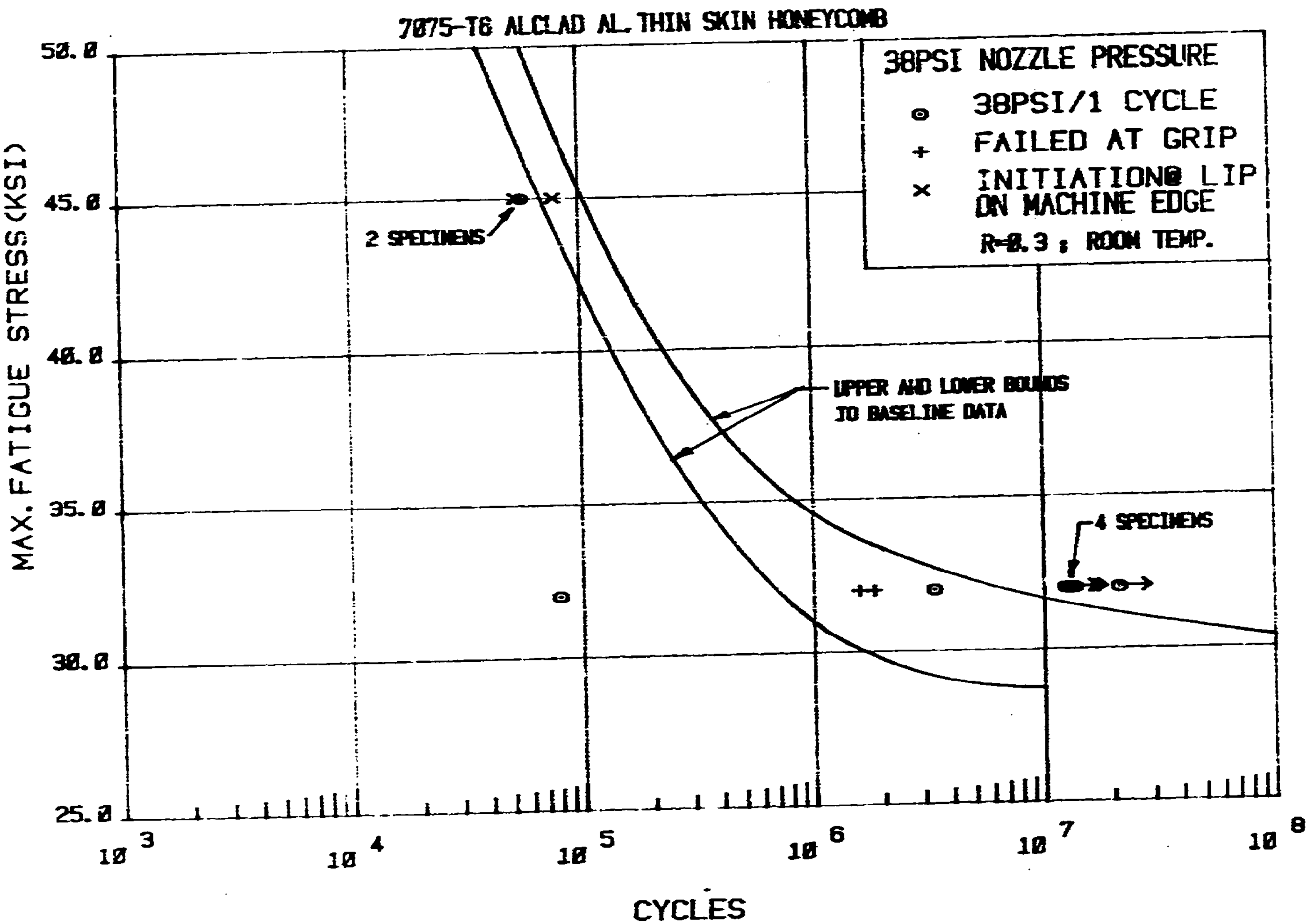


Figure A2. Fatigue Results After One Paint Removal at 38 psi Nozzle Pressure

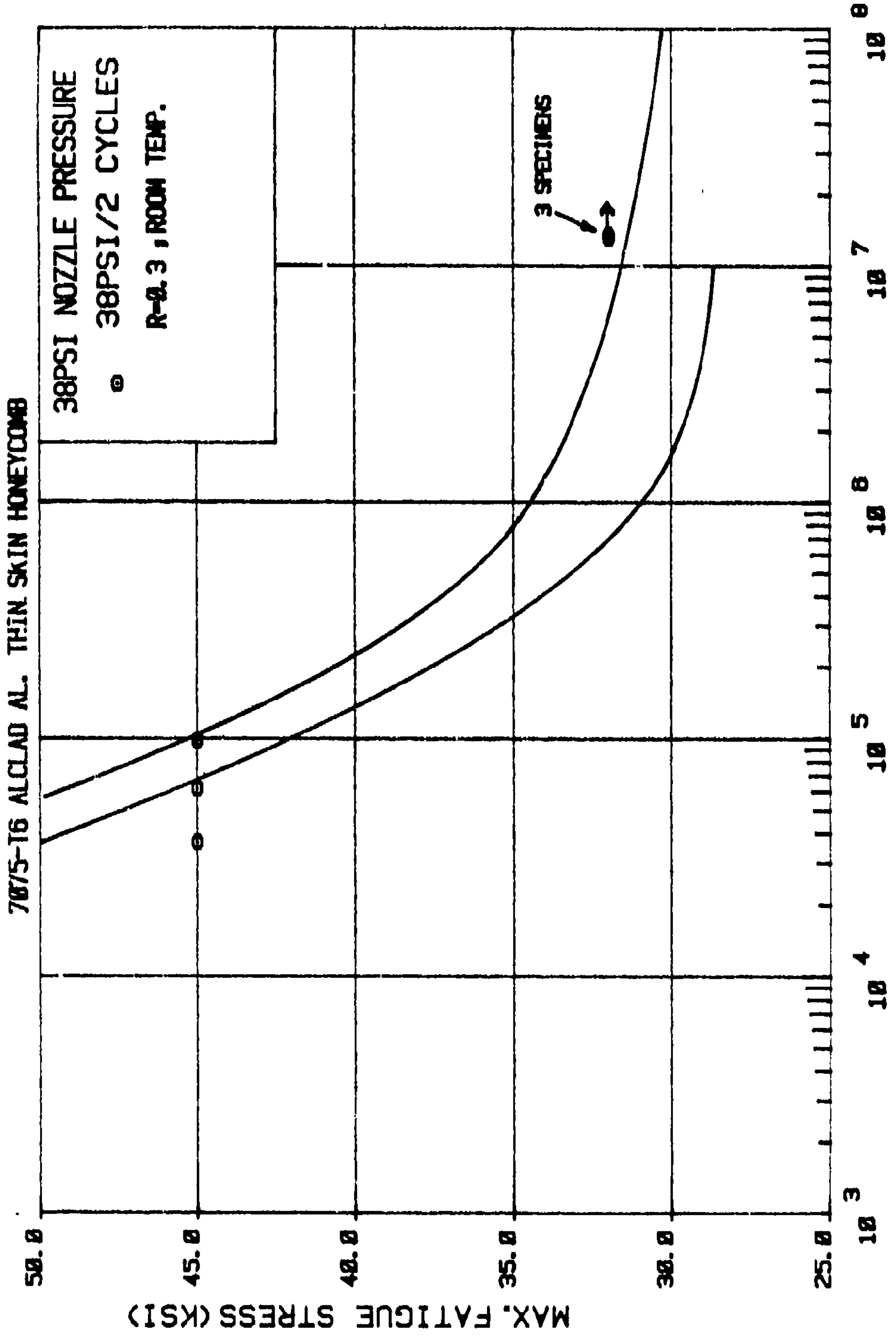


Figure A3. Fatigue Results After Two Paint Removals at 38 psi Nozzle Pressure

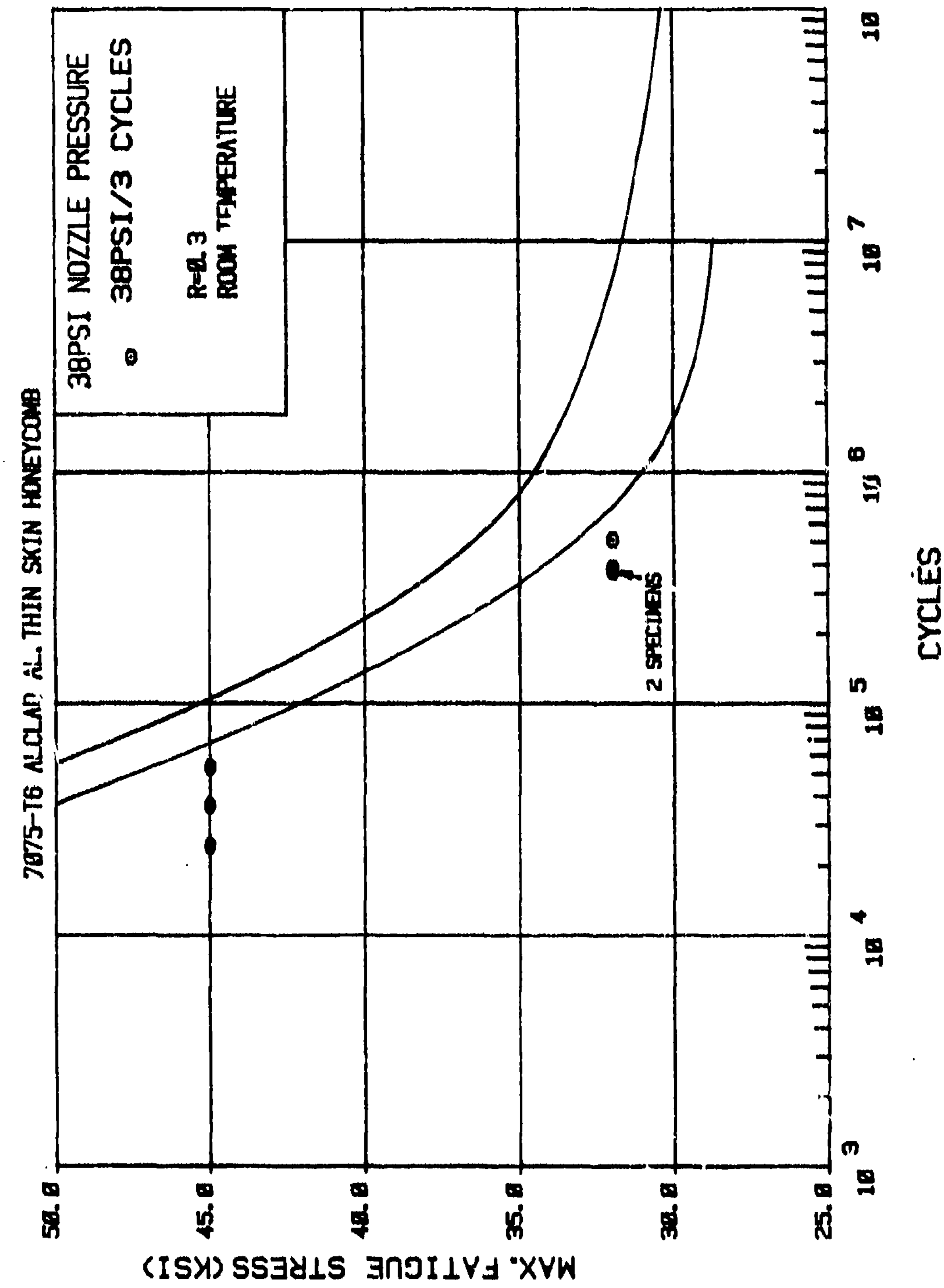


Figure A4. Fatigue Results After Three Paint Removals at 38 psi Nozzle Pressure

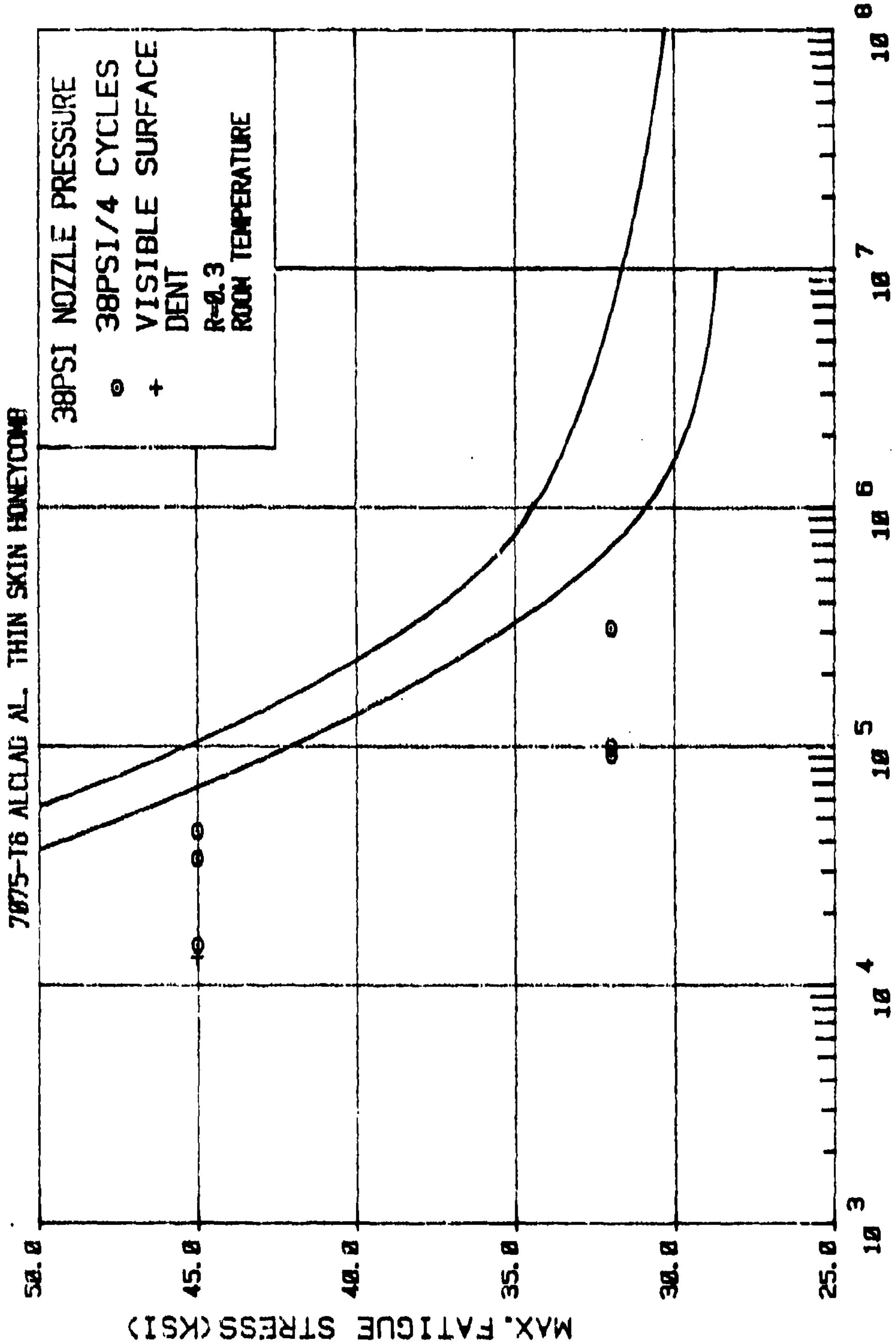


Figure A5. Fatigue Results After Four Paint Removals at 38 psi Nozzle Pressure

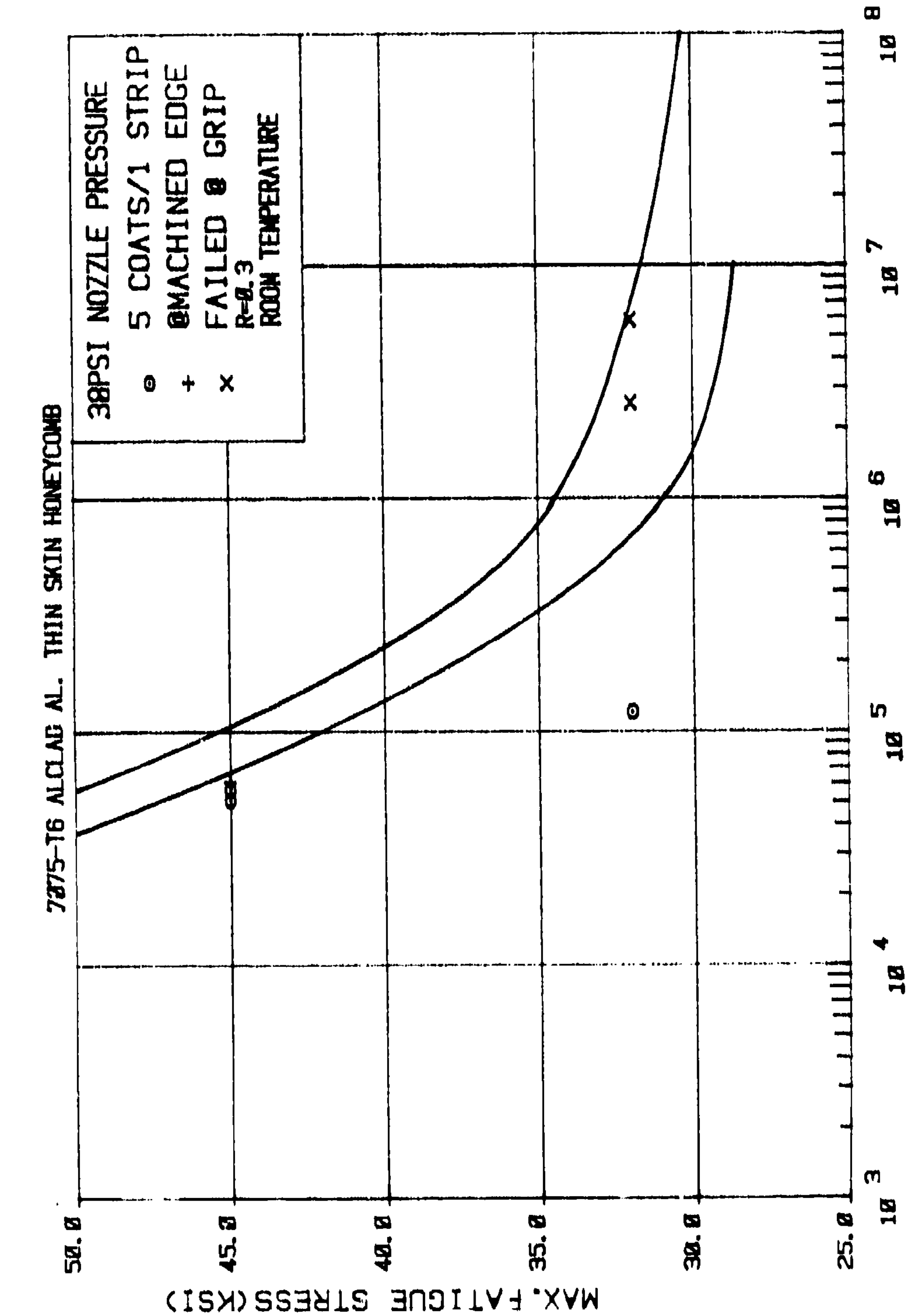


Figure A6. Fatigue Results After One Paint Removal of Five Coats of Paint at 38 psi Nozzle Pressure

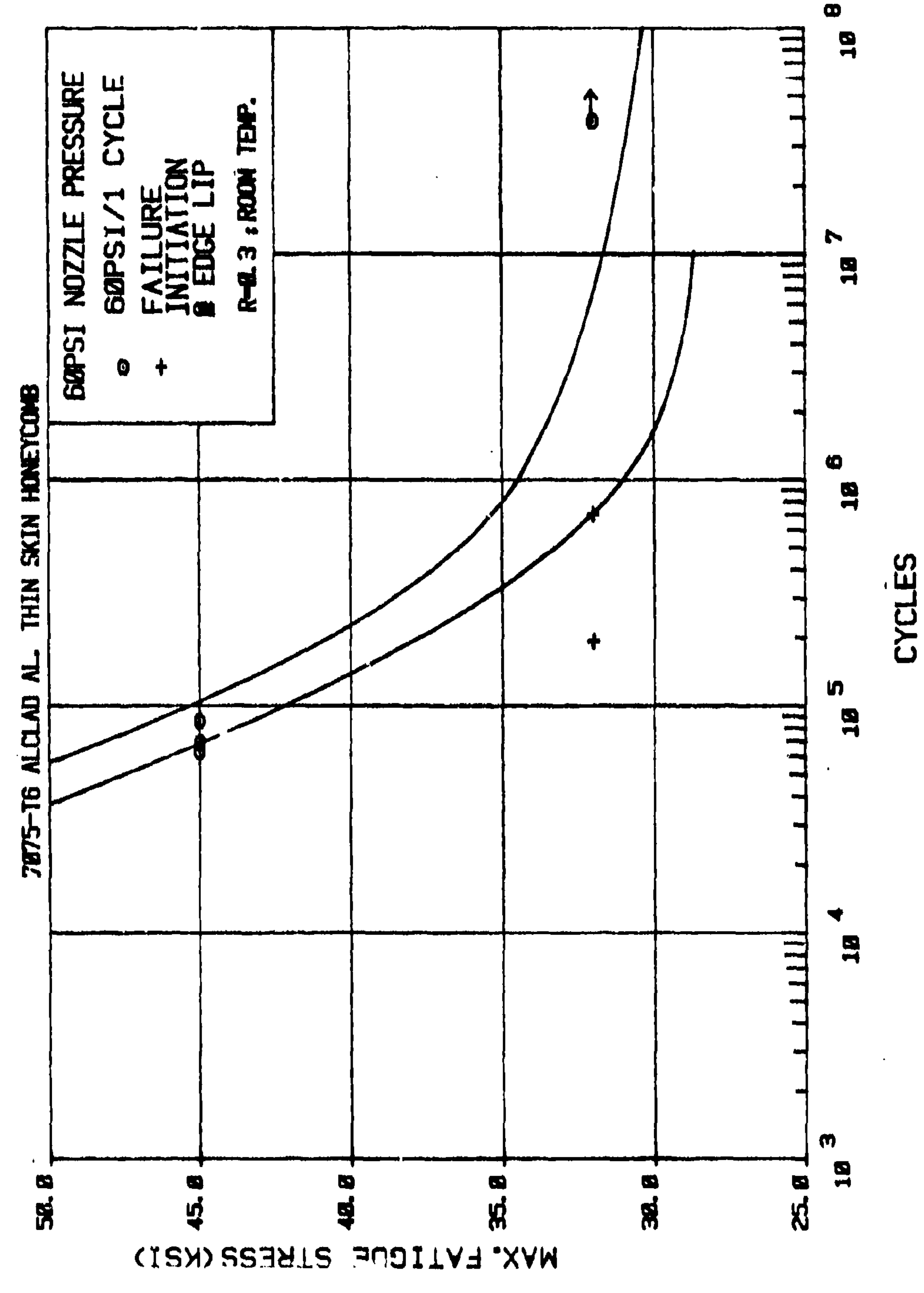


Figure A7. Fatigue Results After One Paint Removal at 60 psi Nozzle Pressure

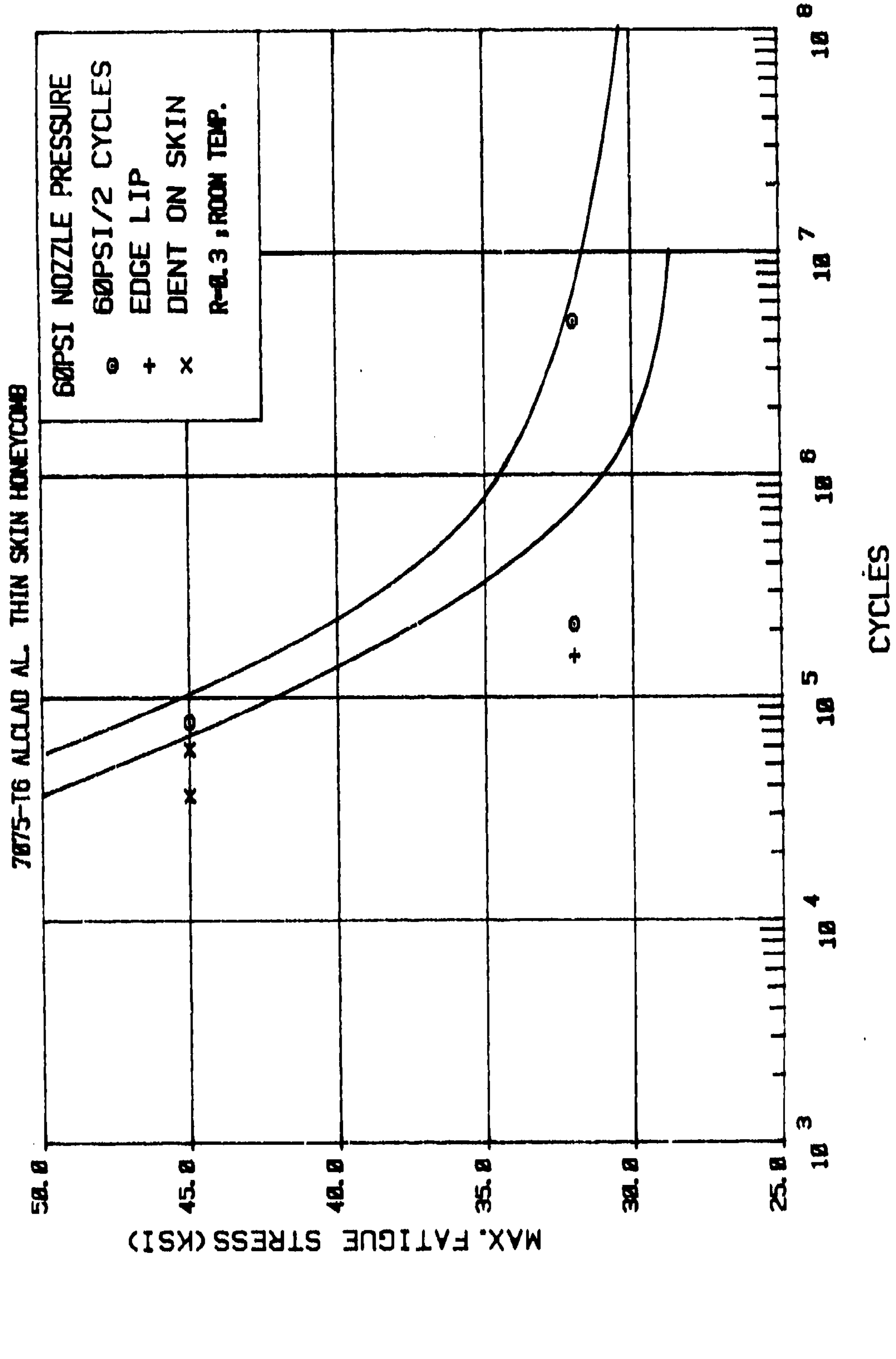


Figure A8. Fatigue Results After Two Paint Removals at 60 psi Nozzle Pressure

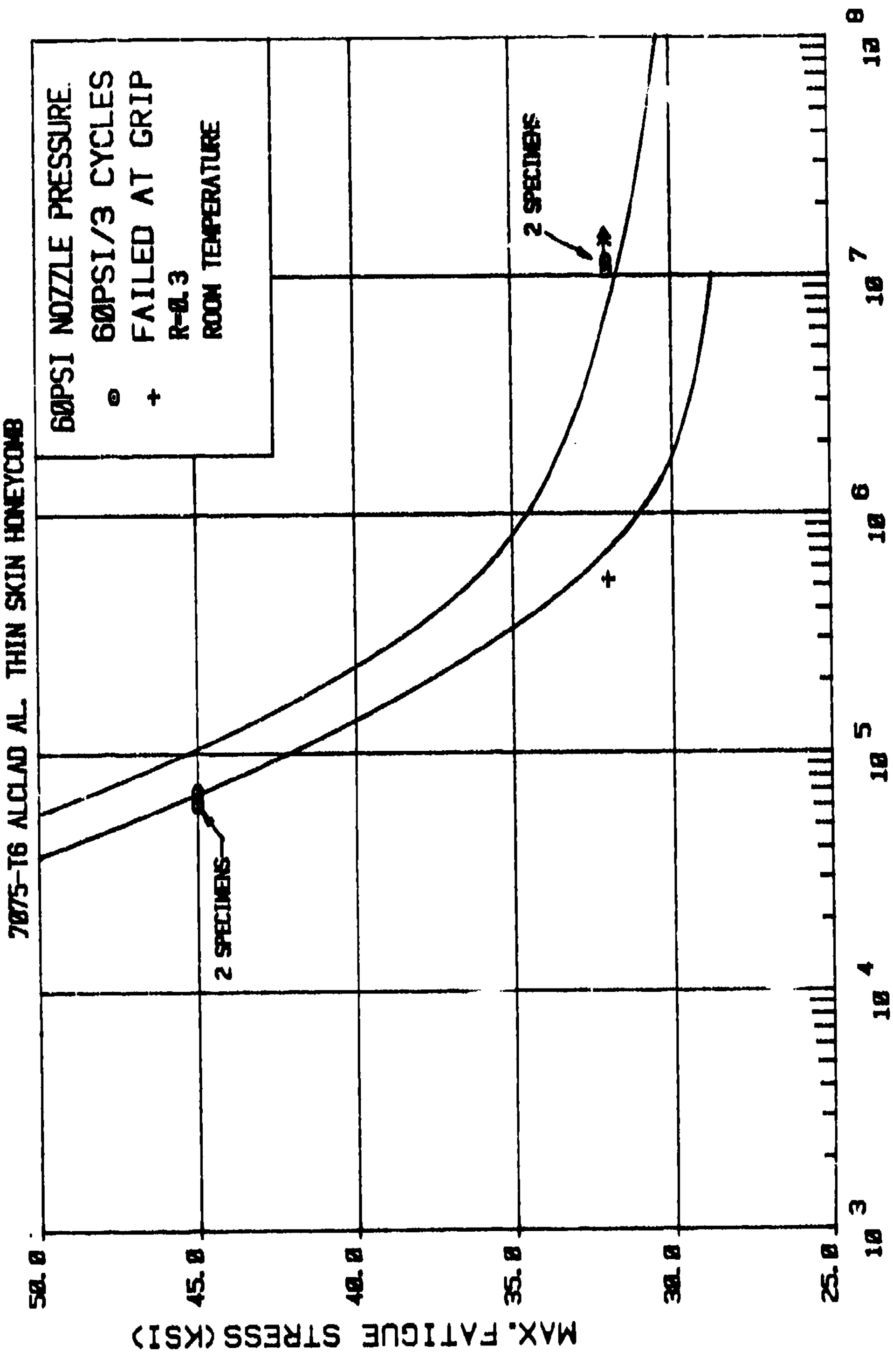


Figure A9. Fatigue Results After Three Paint Removals at 60 psi Nozzle Pressure

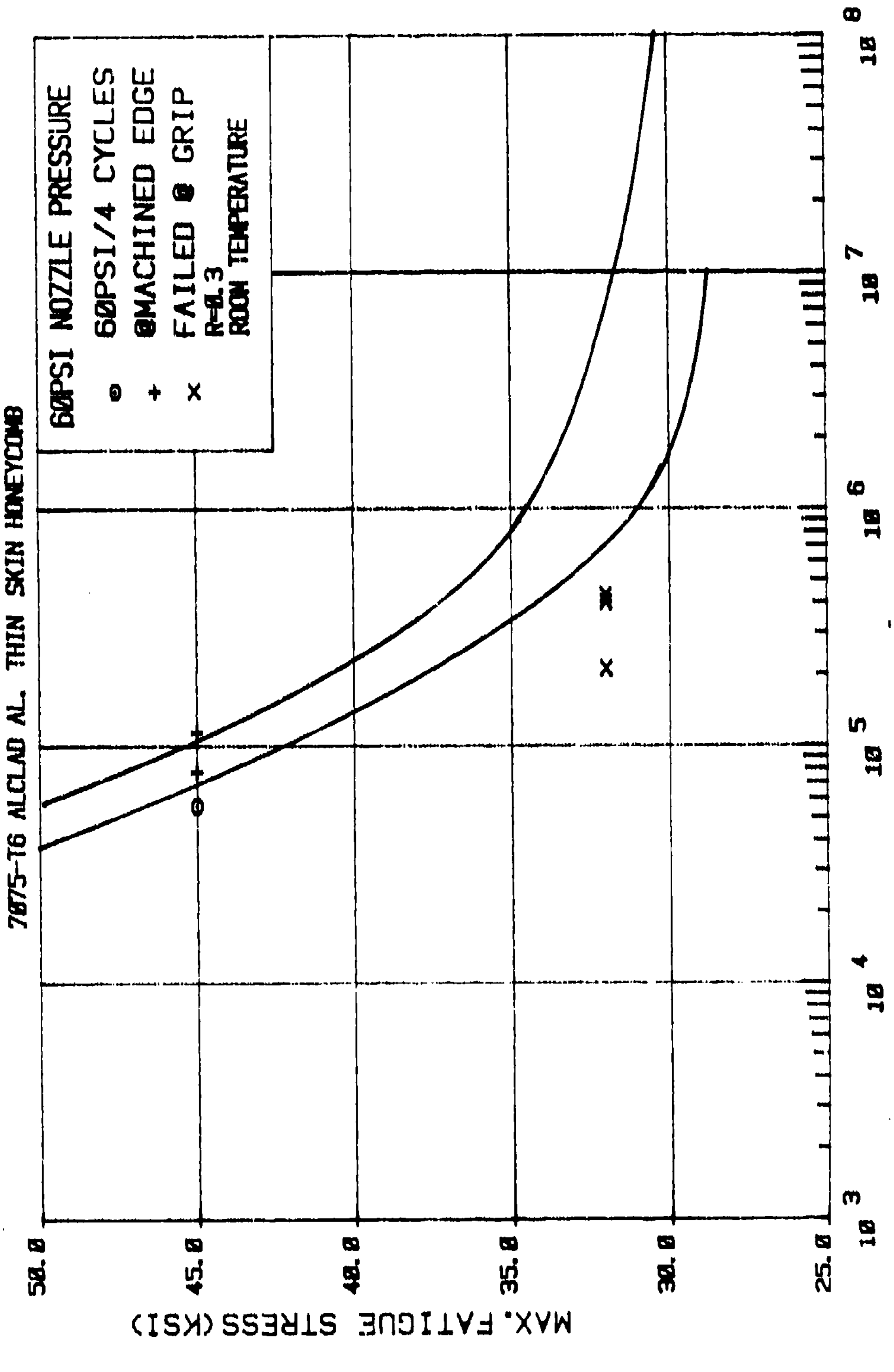


Figure A10. Fatigue Results After Four Paint Removals at 60 psi Nozzle Pressure

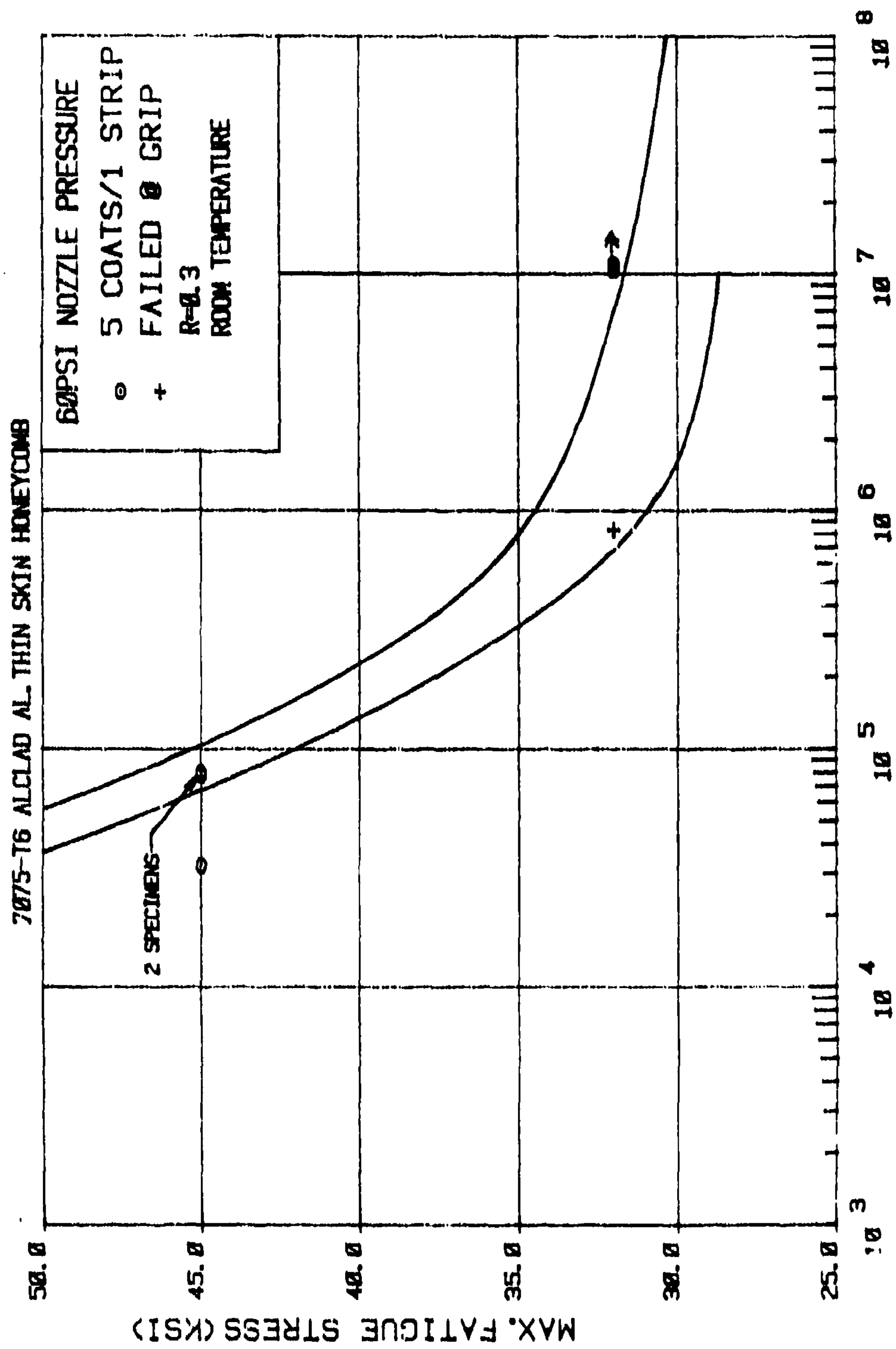


Figure A11. Fatigue Results After One Paint Removal of Five Coats of Paint at 60 psi Nozzle Pressure

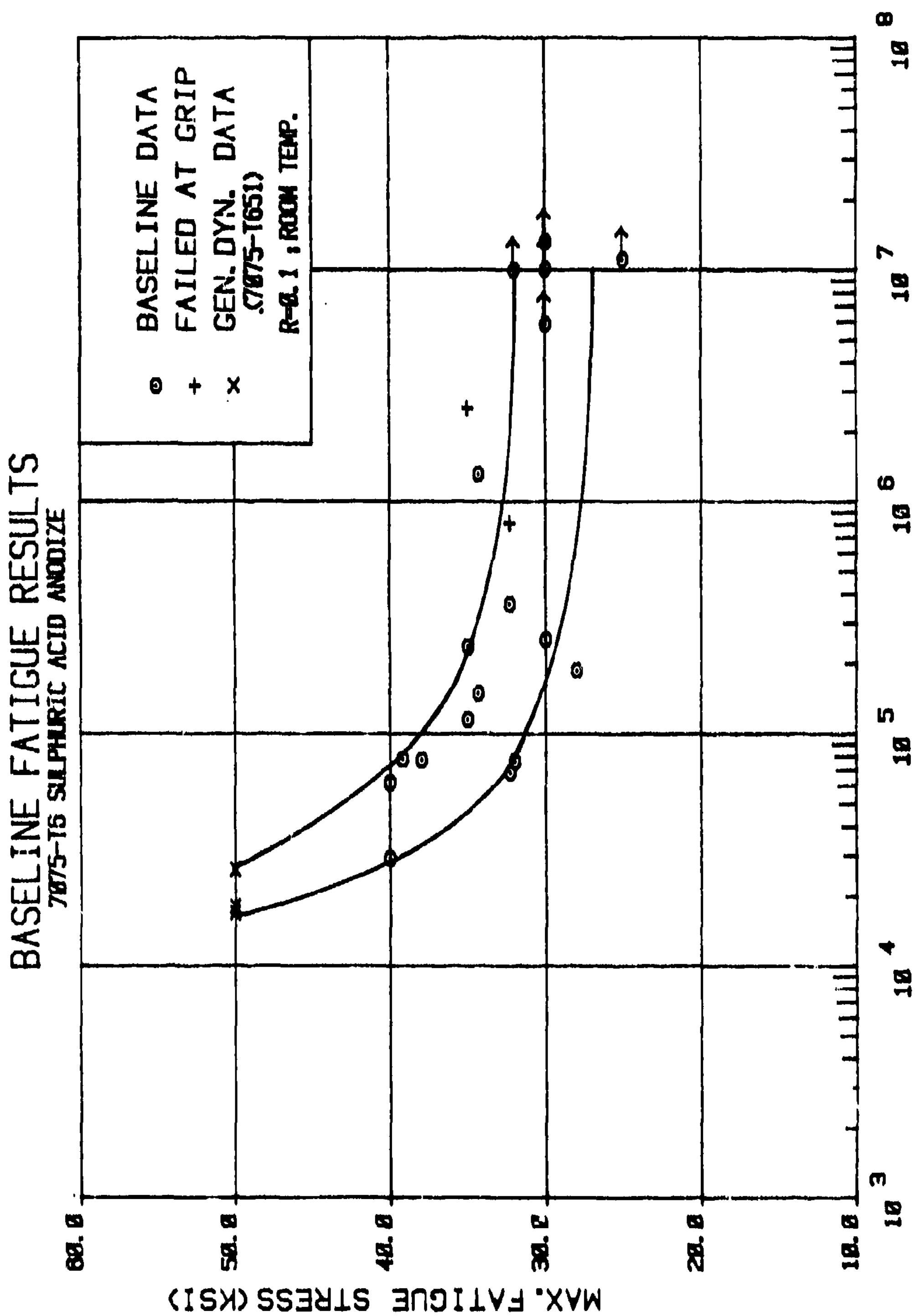


Figure A12. Baseline Fatigue Results on 7075-T6 Sulfuric Acid Anodized Material

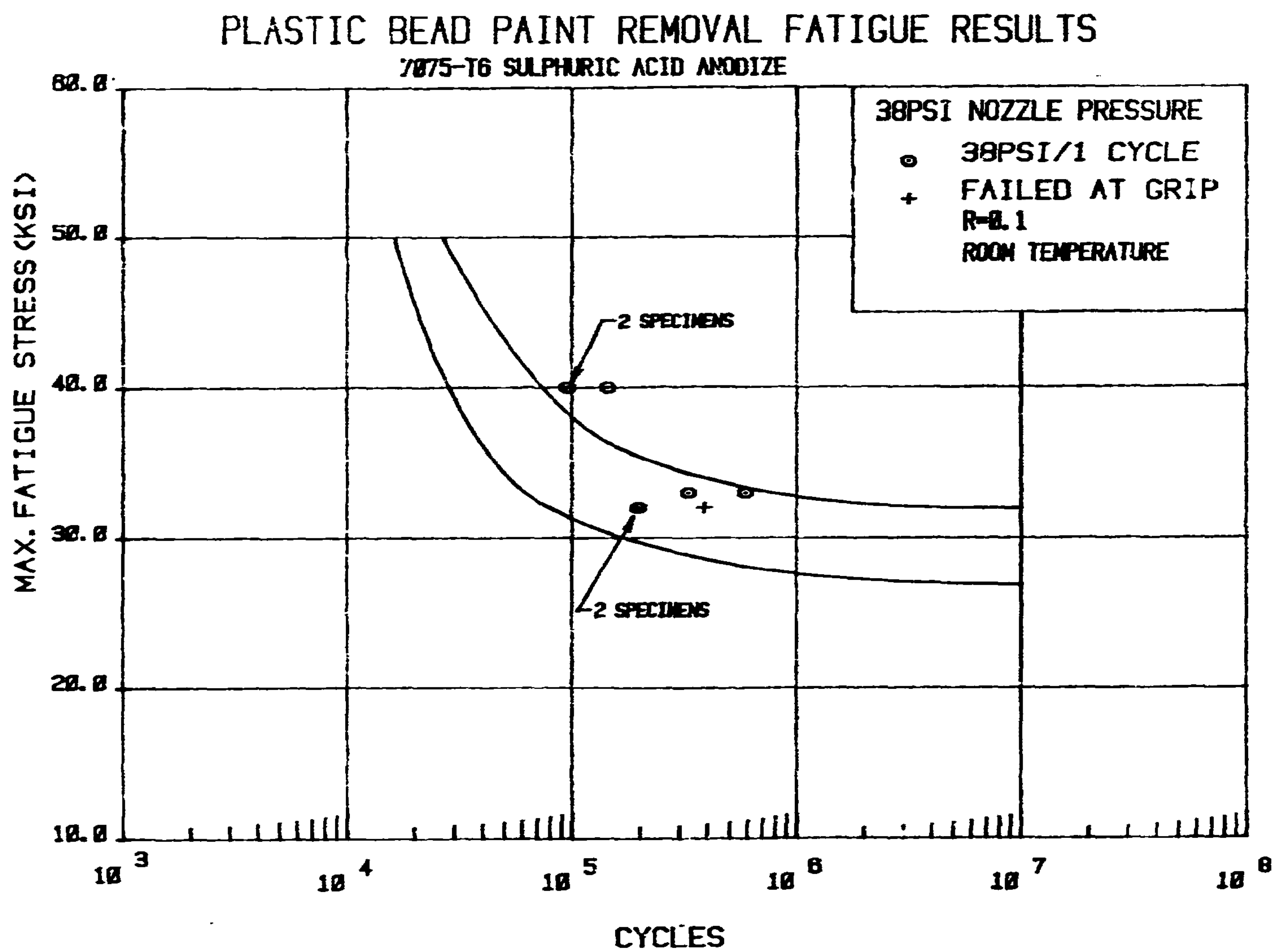


Figure A13. Fatigue Results After One Paint Removal at 38 psi Nozzle Pressure

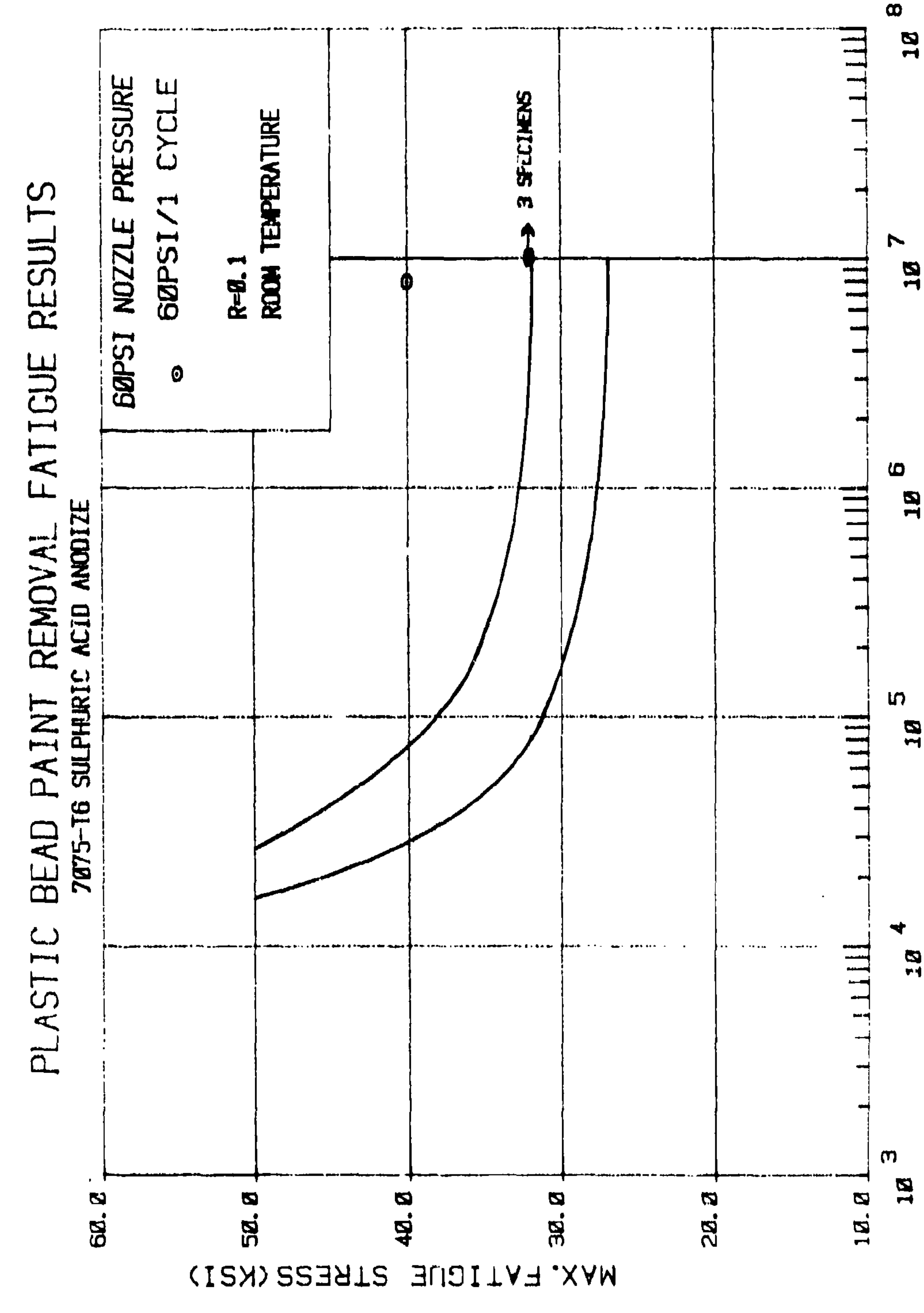


Figure A14. Fatigue Results After One Paint Removal at 60 psi Nozzle Pressure

TABLE A1
FATIGUE RESULTS FROM BASE MATERIAL

Material: 7075-T6 Alclad Aluminum Thin Skin Honeycomb
Test Condition: Room Temperature; Stress Ratio (R) = 0.3

Specimen Number	Max. Stress (KSI)	Fatigue Life (Kilocycles)	Remarks
4B	50	33.3	crack initiation at machined edge
3A	50	55.2	
5B	45	68.5	crack initiation at machined edge
6A	45	96.0	crack initiation at machined edge
6B	45	98.5	crack initiation at machined edge
7A	40	146.0	
1B	40	172.0	crack initiation at machined edge
5A	36	262.0	
7B	34	574.0	
4A	32	2430.0	crack initiation at lip on machined edge
8A	32	783.0	
8B	32	8920.0	
47A	32	360.0	crack initiation at lip on machined edge
47B	32	5350.0	crack initiation at machined edge
3B	30	10500.0	did not fail

TABLE A2
FATIGUE RESULTS AFTER PAINT REMOVAL USING
38 PSI NOZZLE PRESSURE

Material: 7075-T6 Alclad Aluminum Thin Skin Honeycomb
Test Condition: Room Temperature; Stress Ratio (R) = 0.3

Specimen Number	Max. Stress (KSI)	Fatigue Life (Kilocycles)	Remarks
		1 PAINT REMOVAL	
14B	45	78.0	crack initiation at lip on machined edge
17B	45	56.7	
12B	45	53.9	crack initiation at lip on machined edge
14A	32	21200.0	did not fail
12A	32	1830.0	failed at bonded grip tab
17A	32	79.7	
31A	32	12900.0	did not fail
31B	32	3350.0	
55A	32	13500.0	did not fail
55B	32	1580.0	failed at bonded grip tab
33A	32	12400.0	did not fail
33B	32	13600.0	did not fail
		2 PAINT REMOVALS	
32B	45	61.8	
34B	45	98.2	
53A	45	36.7	
32A	32	13100.0	did not fail
34A	32	13300.0	did not fail
53B	32	13500.0	did not fail
		3 PAINT REMOVALS	
24A	45	24.4	
18A	45	53.4	crack initiation at flaw on machined edge
9B	45	36.4	crack initiation at flaw on machined edge
24B	32	385.0	
18B	32	370.0	
9A	32	511.0	crack initiation at flaw on machined edge

TABLE A2 - Continued

Specimen Number	Max. Stress (KSI)	Fatigue Life (Kilocycles)	Remarks
		4 PAINT REMOVALS	
10B	45	14.7	
38B	45	13.1	crack initiation at visible surface dent
48B	45	33.9	
67A	45	44.3	
10A	32	92.1	
38A	32	310.0	
67B	32	100.0	
48A	32	10554.0	did not fail
		1 PAINT REMOVAL OF 5 COATS OF PAINT	
45B	45	61.0	crack initiation at flaw on machined edge
58A	45	51.0	
36B	45	56.5	
45A	32	5810.0	failed at bonded grip tab
36A	32	121.0	
58B	32	2560.0	failed at bonded grip tab

TABLE A3
FATIGUE RESULTS AFTER PAINT REMOVAL USING
60 PSI NOZZLE PRESSURE

Material: 7075-T6 Alclad Aluminum Thin Skin Honeycomb
Test Condition: Room Temperature; Stress Ratio (R) = 0.3

Specimen Number	Max. Stress (KSI)	Fatigue Life (Kilocycles)	Remarks
		1 PAINT REMOVAL	
13A	45	85.6	
41B	45	62.9	
42A	45	69.4	
13B	32	193.0	crack initiation at lip on machined edge
41A	32	38600.0	did not fail
42B	32	703.0	crack initiation at lip on machined edge
		2 PAINT REMOVALS	
11B	45	36.5	crack initiation at visible surface dent
50B	45	78.0	
65B	45	58.8	crack initiation at visible surface dent
11A	32	4910.0	
50A	32	153.0	crack initiation at lip on machined edge
65A	32	213.0	crack initiation at lip on machined edge
		3 PAINT REMOVALS	
51A	45	61.7	
61A	45	60.6	
66A	45	68.9	
51B	32	11400.0	did not fail
61B	32	10600.0	did not fail
66B	32	528.0	failed at bonded grip tab

TABLE A3 - Continued

Specimen Number	Max. Stress (KSI)	Fatigue Life (Kilocycles)	Remarks
		4 PAINT REMOVALS	
35B	45	56.0	
57B	45	114.0	crack initiation at flaw on machined edge
63B	45	77.9	crack initiation at flaw on machined edge
35A	32	211.0	failed at bonded grip tab
57A	32	403.0	failed at bonded grip tab
63A	32	430.0	failed at bonded grip tab
		1 PAINT REMOVAL OF 5 COATS OF PAINT	
52B	45	32.4	
59B	45	79.5	
60B	45	77.9	
52A	32	832.0	failed at bonded grip tab
59A	32	10400.0	did not fail
60A	32	10900.0	did not fail

TABLE A4
FATIGUE RESULTS FROM BASE MATERIAL

Material: 7075-T6 Sulphuric Acid Anodized (.063 Sheet)
Test Condition: Room Temperature; Stress Ratio (R) = 0.1

Specimen Number	Max. Stress (KSI)	Fatigue Life (Kilocycles)	Remarks
TB-1	40	29.2	crack initiation at machine edge
LB-7	40	61.7	
LB-14	39.2	77.9	crack initiation at machine edge
LB-11	38	77.1	crack initiation at machine edge
TB-2	35	237.0	
TB-3	35	115.0	
LB-9	35	2530.0	failed at bonded grip tab
LB-3	34.3	1310.0	
LB-10	34.3	149.0	crack initiation at machine edge
LB-12	32.3	808.0	failed at bonded grip tab
LB-13	32.3	68.1	crack initiation at machine edge
LB-15	32.3	36.2	
TB-4	32	76.1	crack initiation at machine edge
LB-2	32	10000.0	did not fail
TB-2	30	5840.0	did not fail
LB-1	30	254.0	
LB-5	30	10100.0	did not fail
LB-8	30	13200.0	did not fail
LB-4	28	187.0	crack initiation at machine edge
LB-5	25	11100.0	did not fail

NOTE: For these specimens where the crack initiated at the machine edge, there were no burrs or lips present.

TABLE A5
FATIGUE RESULTS AFTER ONE PAINT REMOVAL USING
38 PSI & 60 PSI NOZZLE PRESSURES

Material: 7075-T6 Sulphuric Acid Anodized (.063 Sheet)
Test Condition: Room Temperature; Stress Ratio (R) = 0.1

Specimen Number	Max. Stress (KSI)	Fatigue Life (Kilocycles)	Remarks
		38 PSI NOZZLE PRESSURE	
SA-1	40	144.0	crack initiation on paint removal side
SA-2	40	94.8	same as above
SA-3	40	95.7	same as above
SA-7	33	589.0	same as above
SA-8	33	328.0	same as above
SA-4	32	196.0	same as above & at machine edge
SA-5	32	388.0	failed at bonded grip tab
SA-6	32	199.0	crack initiation on paint removal side
		60 PSI NOZZLE PRESSURE	
SA-12	40	error in cycles to failure	crack initiation on paint removal side & at machine edge
SA-14	40	7940.0	crack initiation within specimen thickness
SA-9	32	10300.0	did not fail
SA-11	32	10000.0	did not fail
SA-13	32	10000.0	did not fail

APPENDIX B

COMPOSITE DATA

All of the tensile and flexure data generated during this program are shown in this section. These data are shown in both tabular and graphical form.

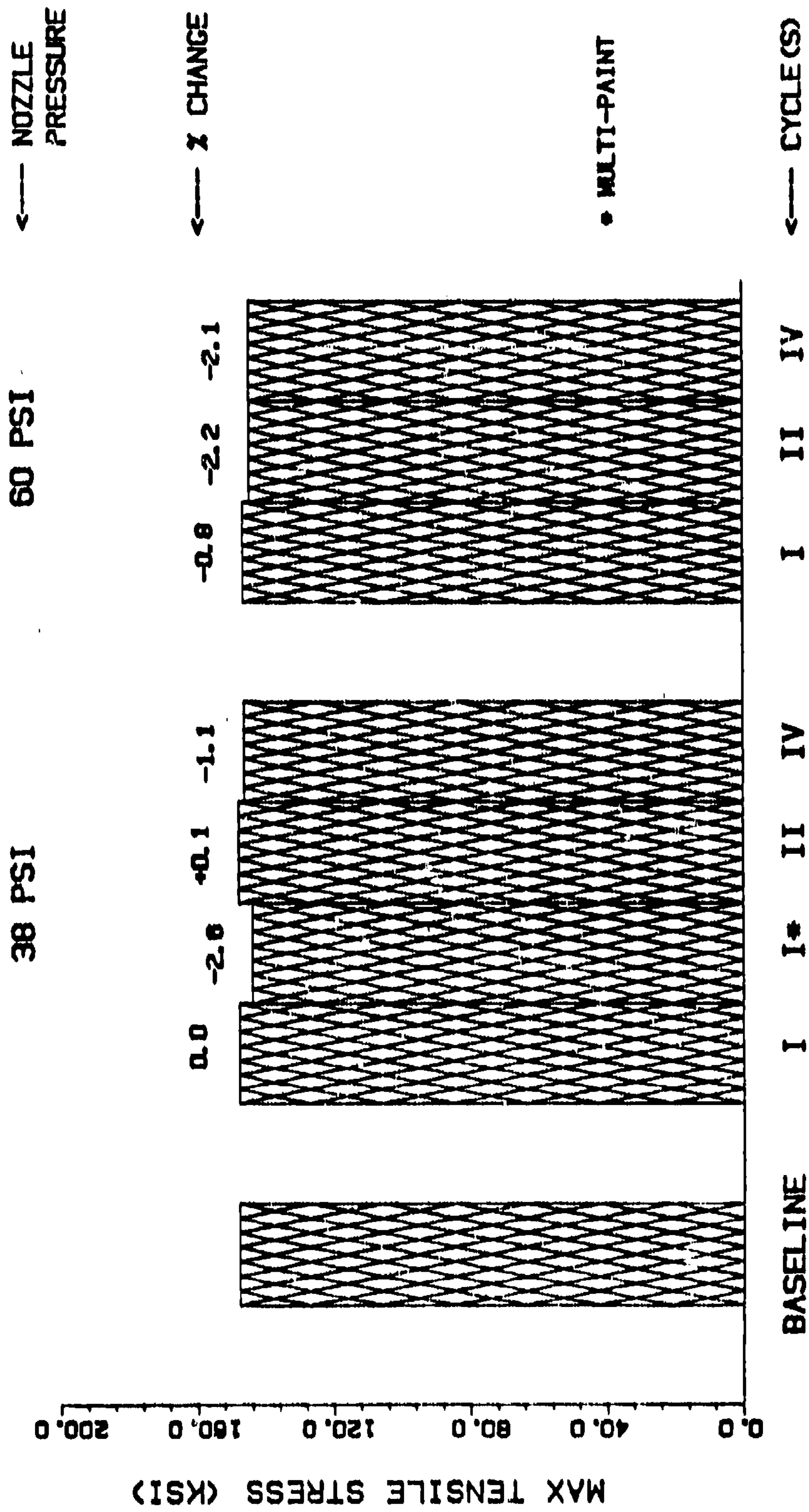


Figure B1. Tensile Strength of AS4/3501-6 with Fiber Orientation [0/±45/0/90/0]s

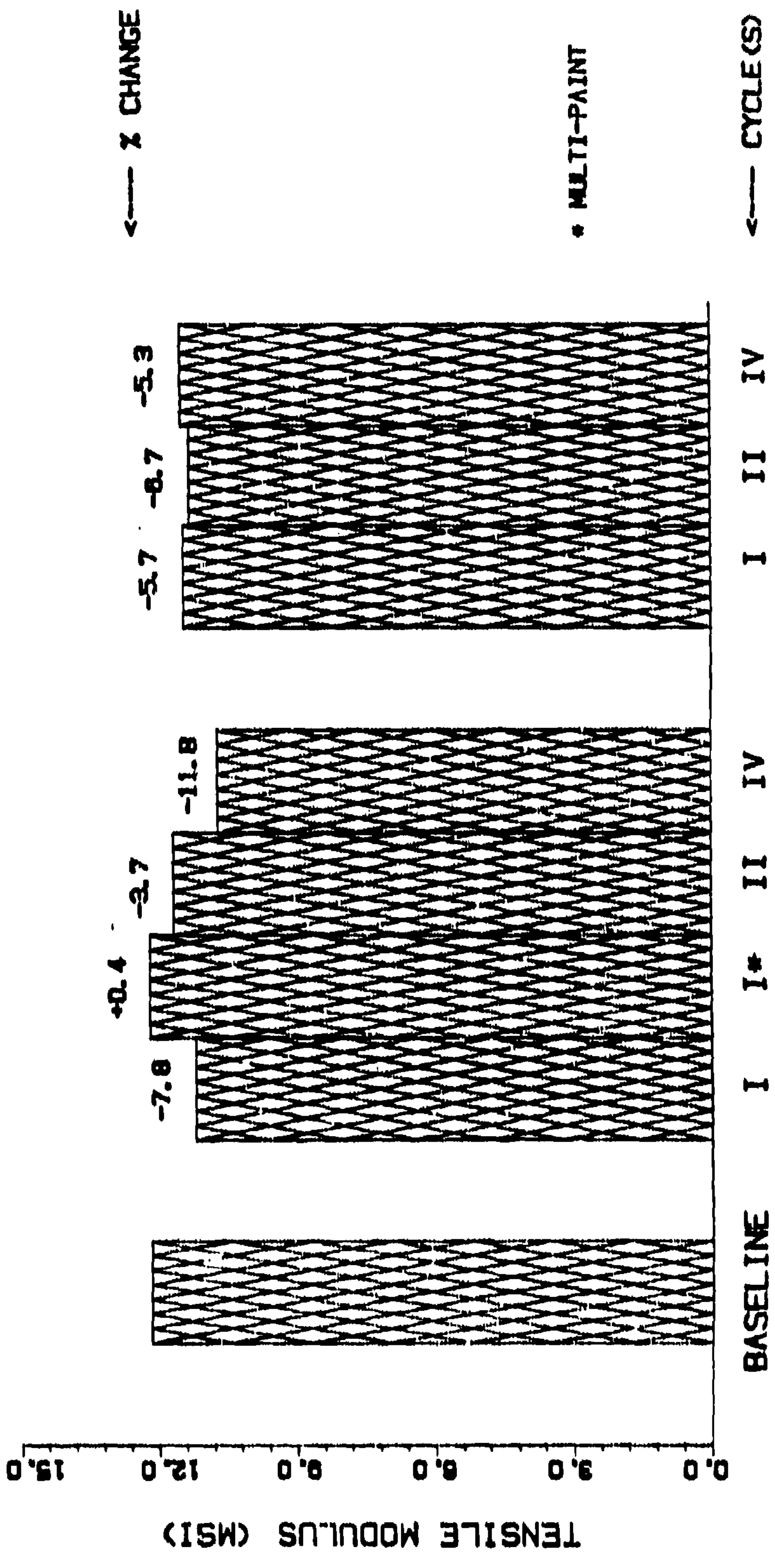


Figure B2. Tensile Modulus of AS4/3501-6 with Fiber Orientation [0/±45/0/90/0]s

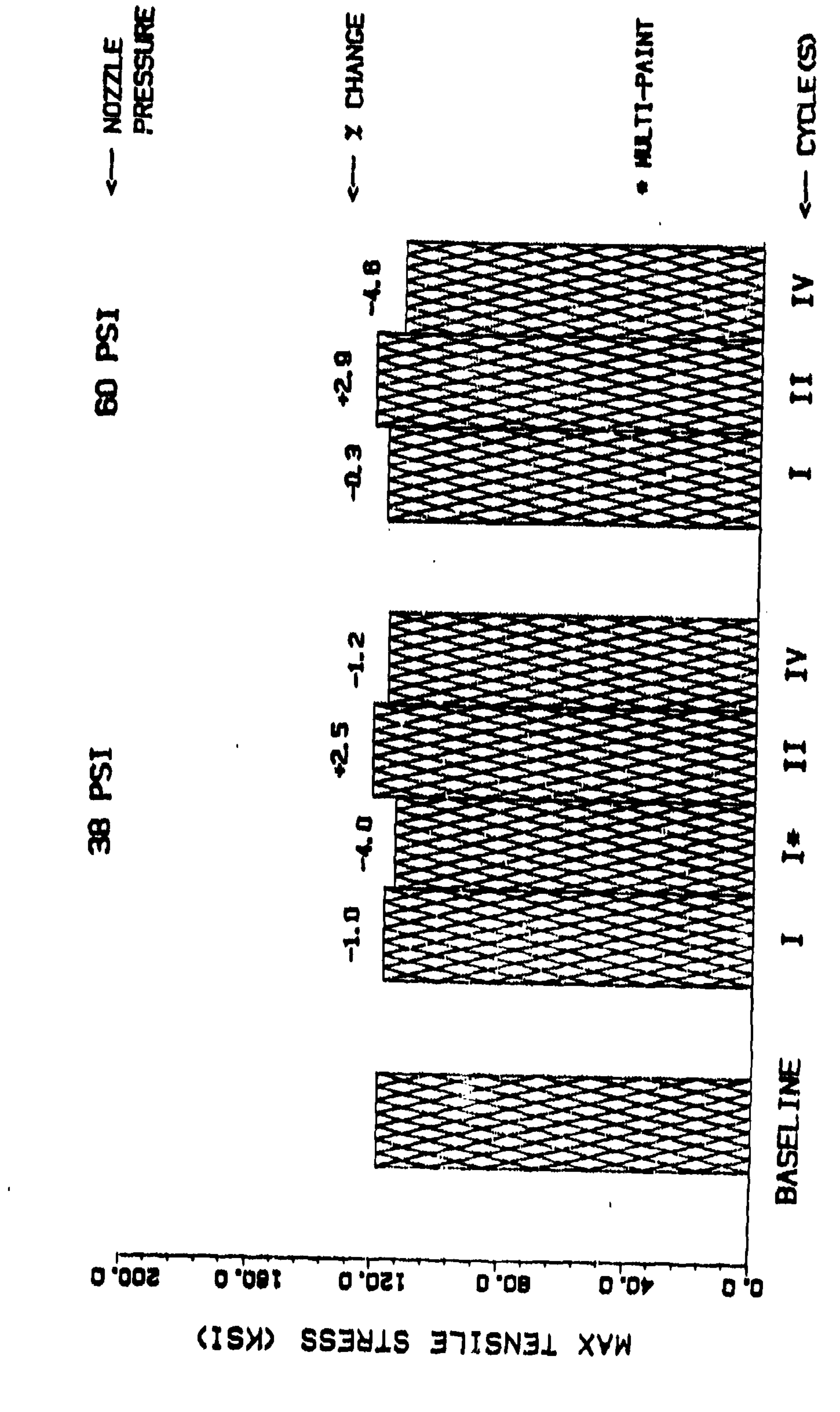


Figure B3. Tensile Strength of AS4/3501-6 with Fiber Orientation [90/0/±45/0/90]

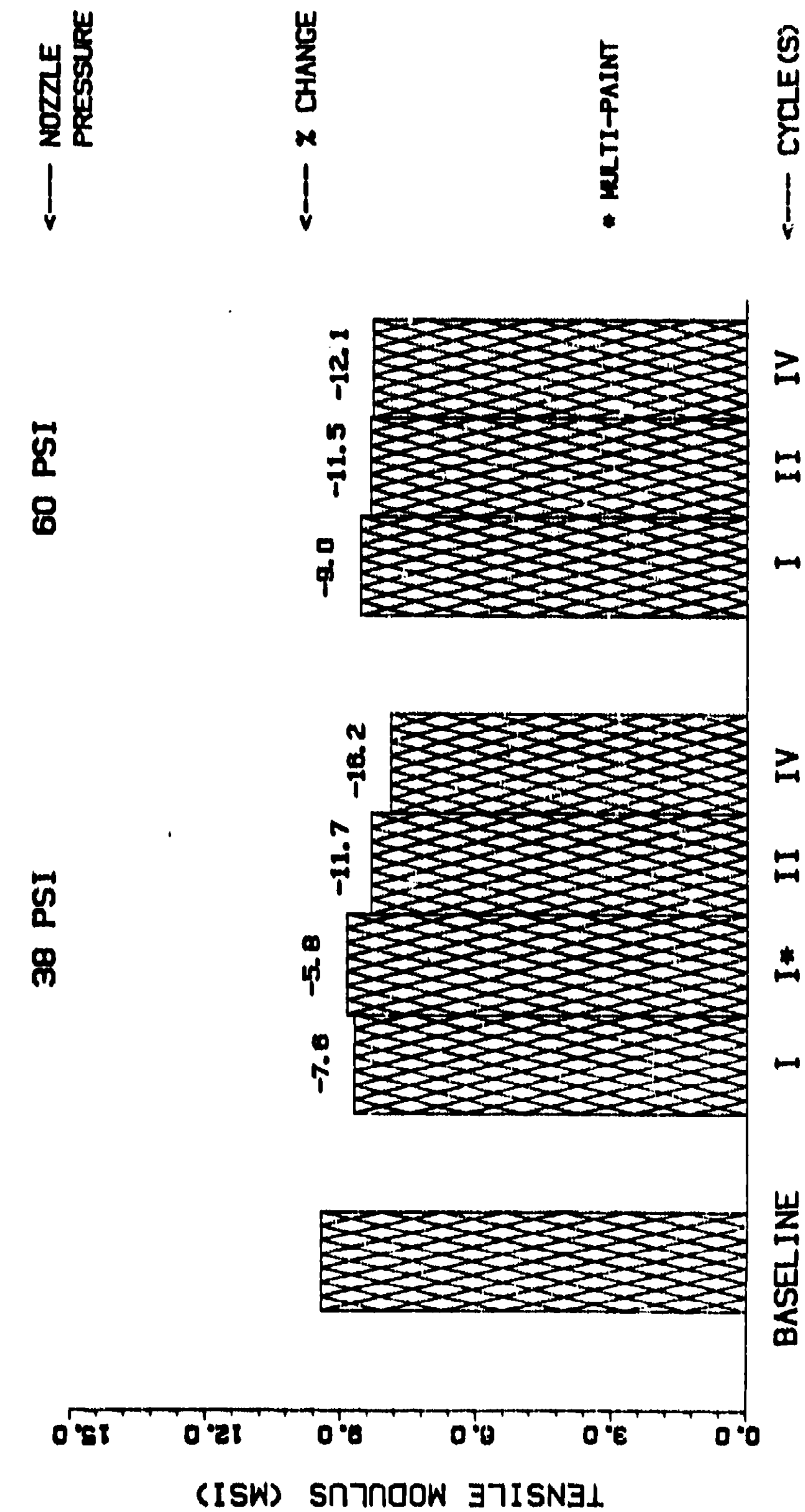


Figure B4. Tensile Modulus of AS4/3501-6 with Fiber Orientation [90/0/±45/0/90]

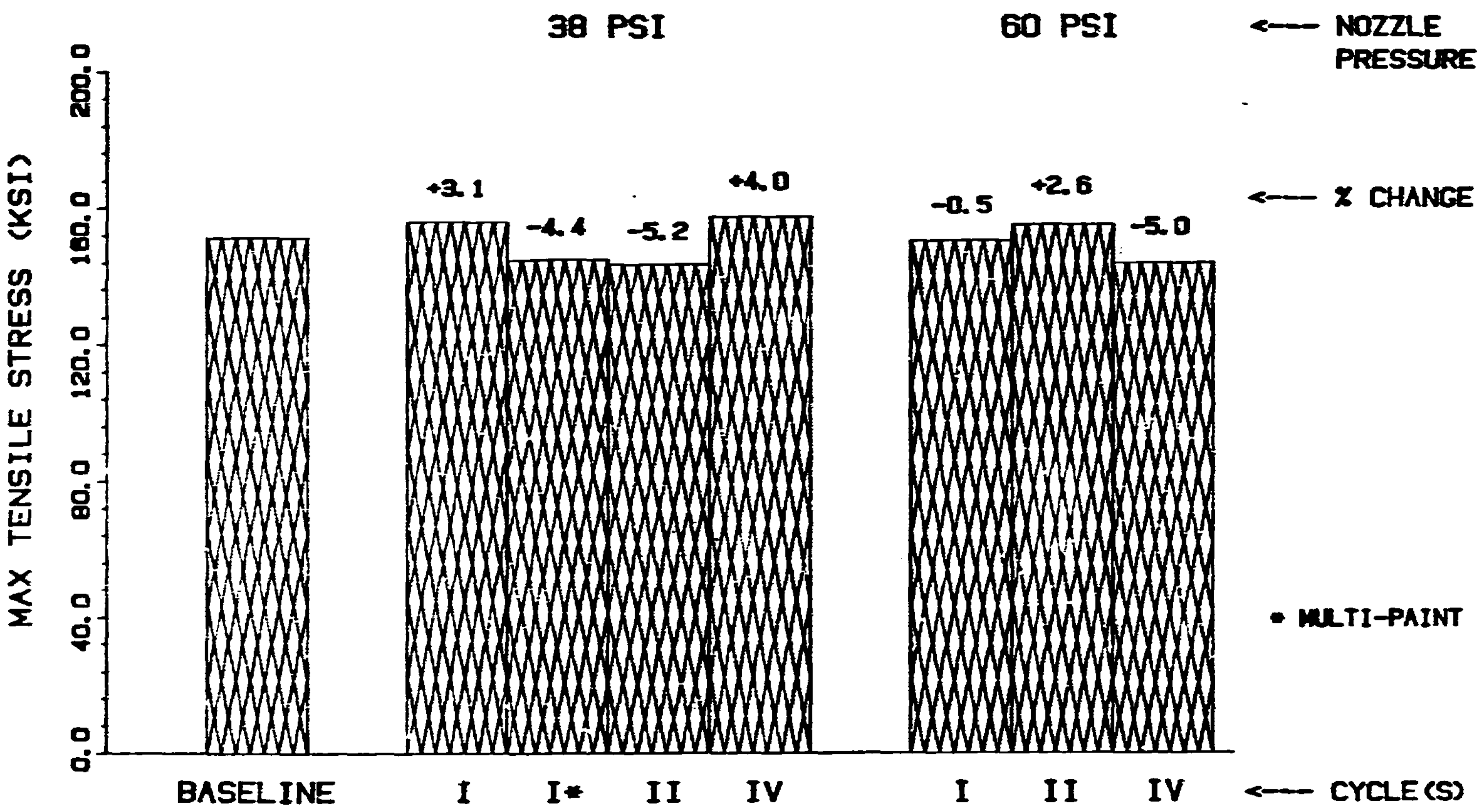


Figure B5. Tensile Strength of AS4/3501-6 with Fiber Orientation [±45/0/0/90/0]s

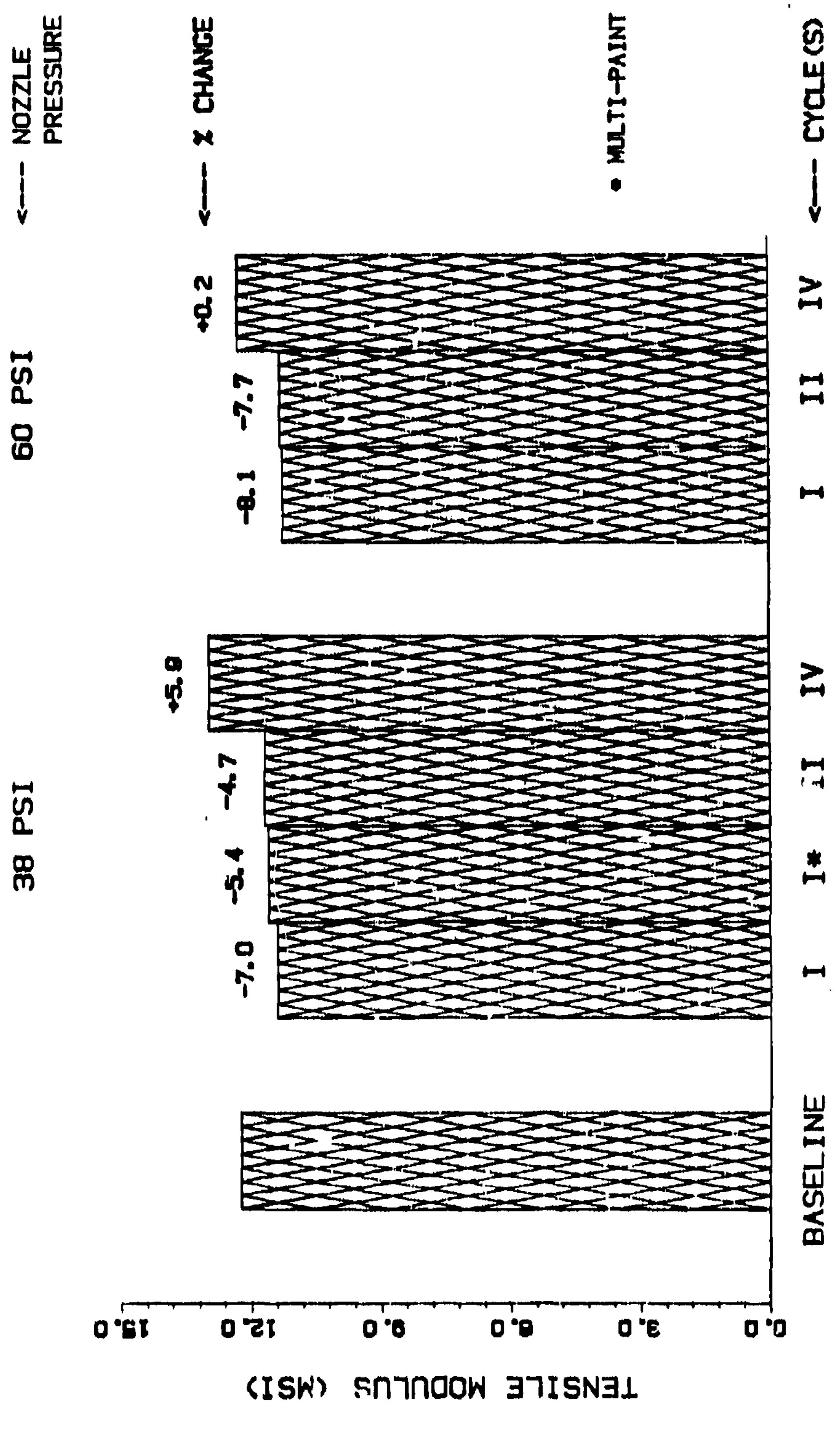


Figure B6. Tensile Modulus of AS4/3501-6 with Fiber Orientation [±45/0/0/90/0]s

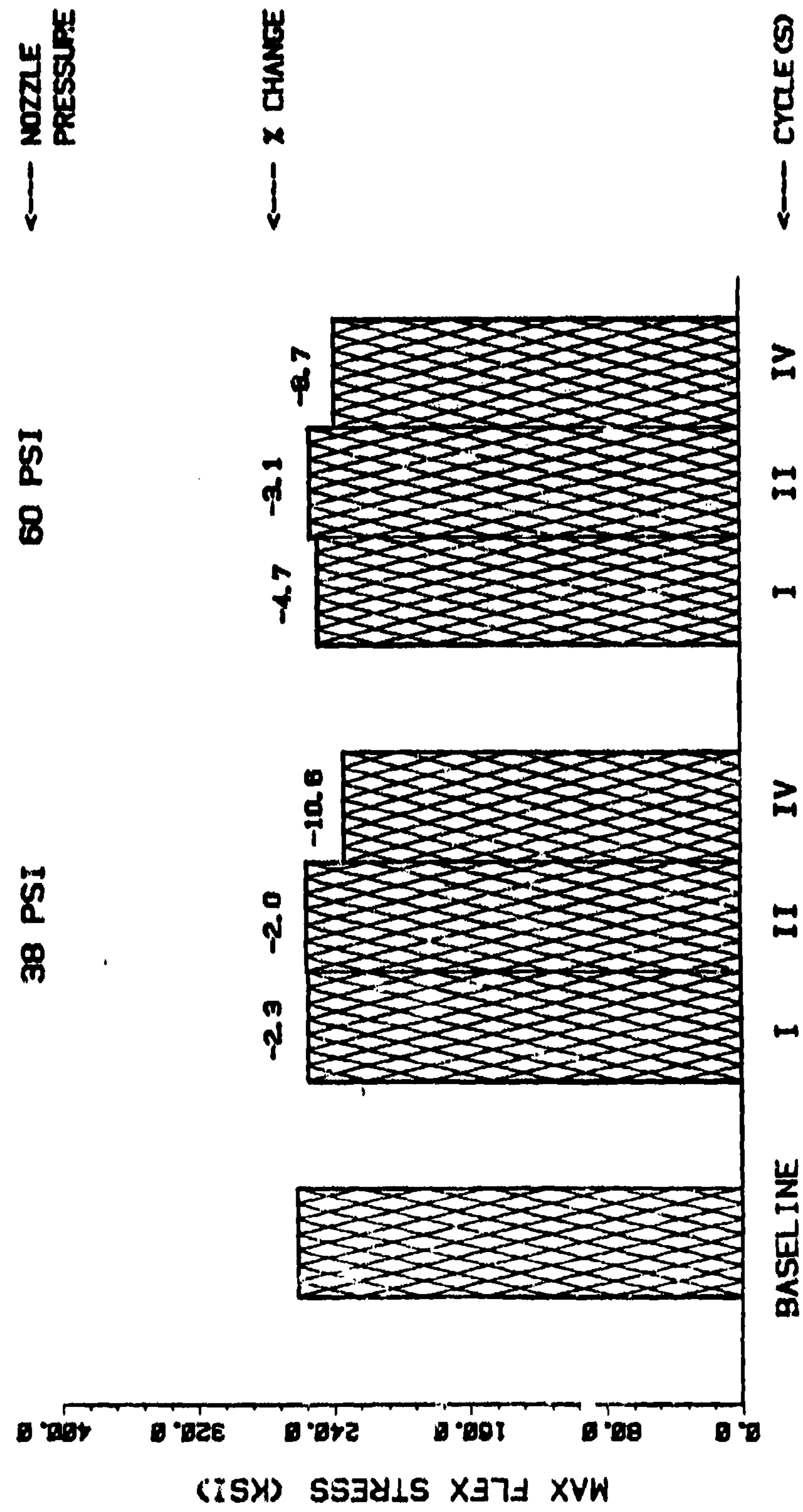


Figure B7. Flexural Strength of AS4/3501-6 with 0° Fiber Orientation

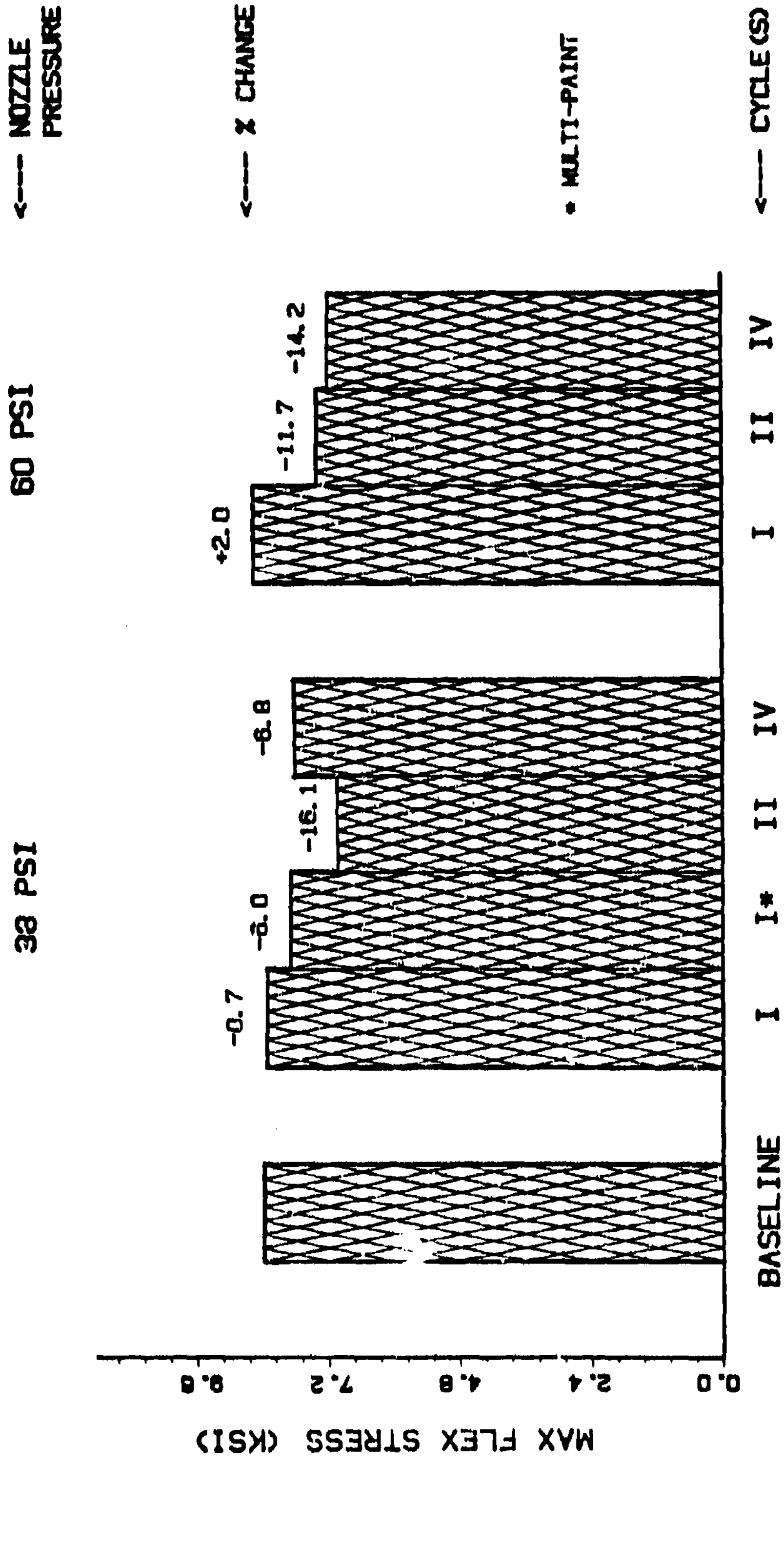


Figure B8. Flexural Strength of AS4/3501-6 with 90° Fiber Orientation

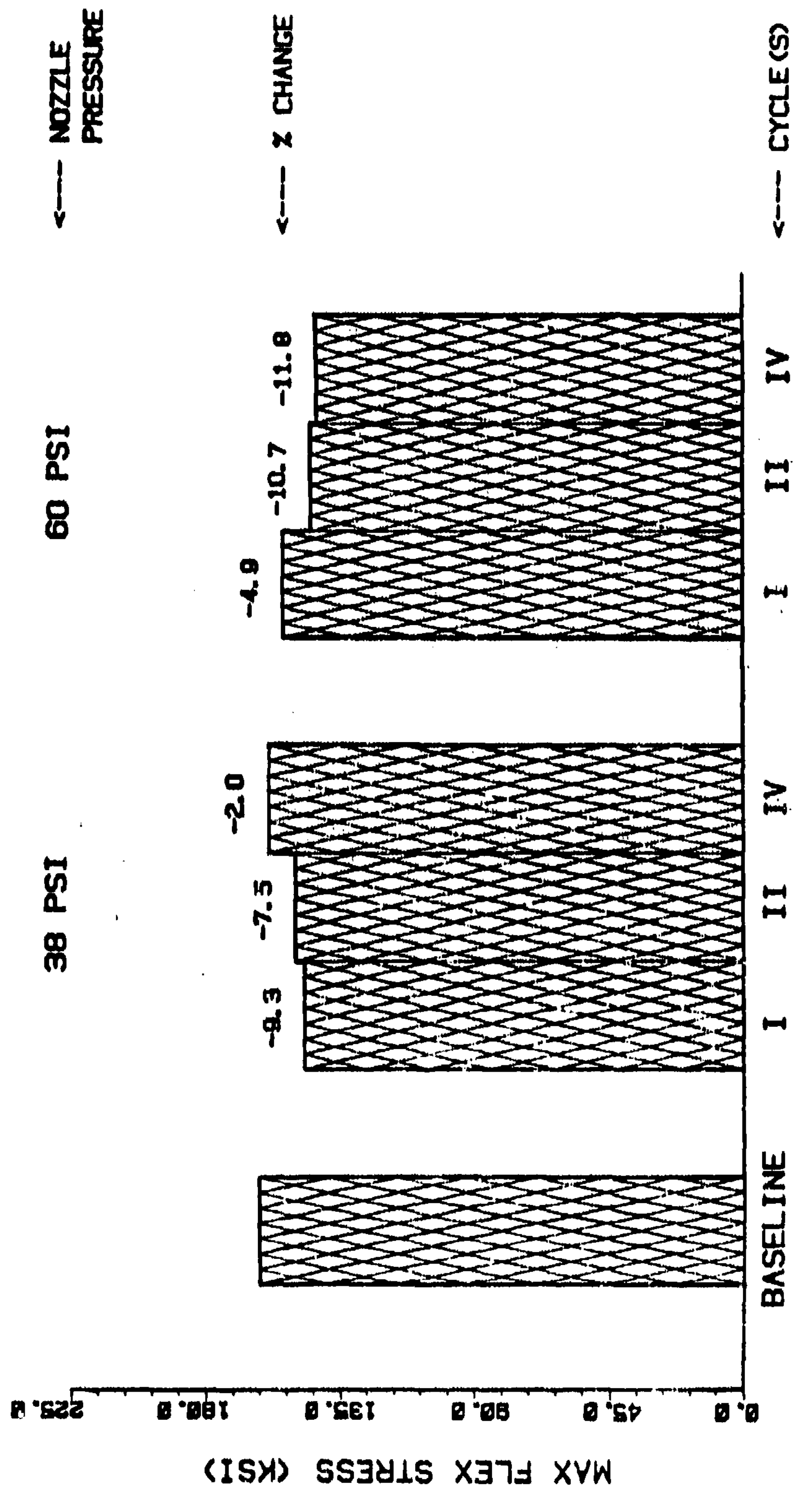


Figure B9. Flexural Strength of AS4/3501-6 with Fiber Orientation [0/±45/0/90/0]s

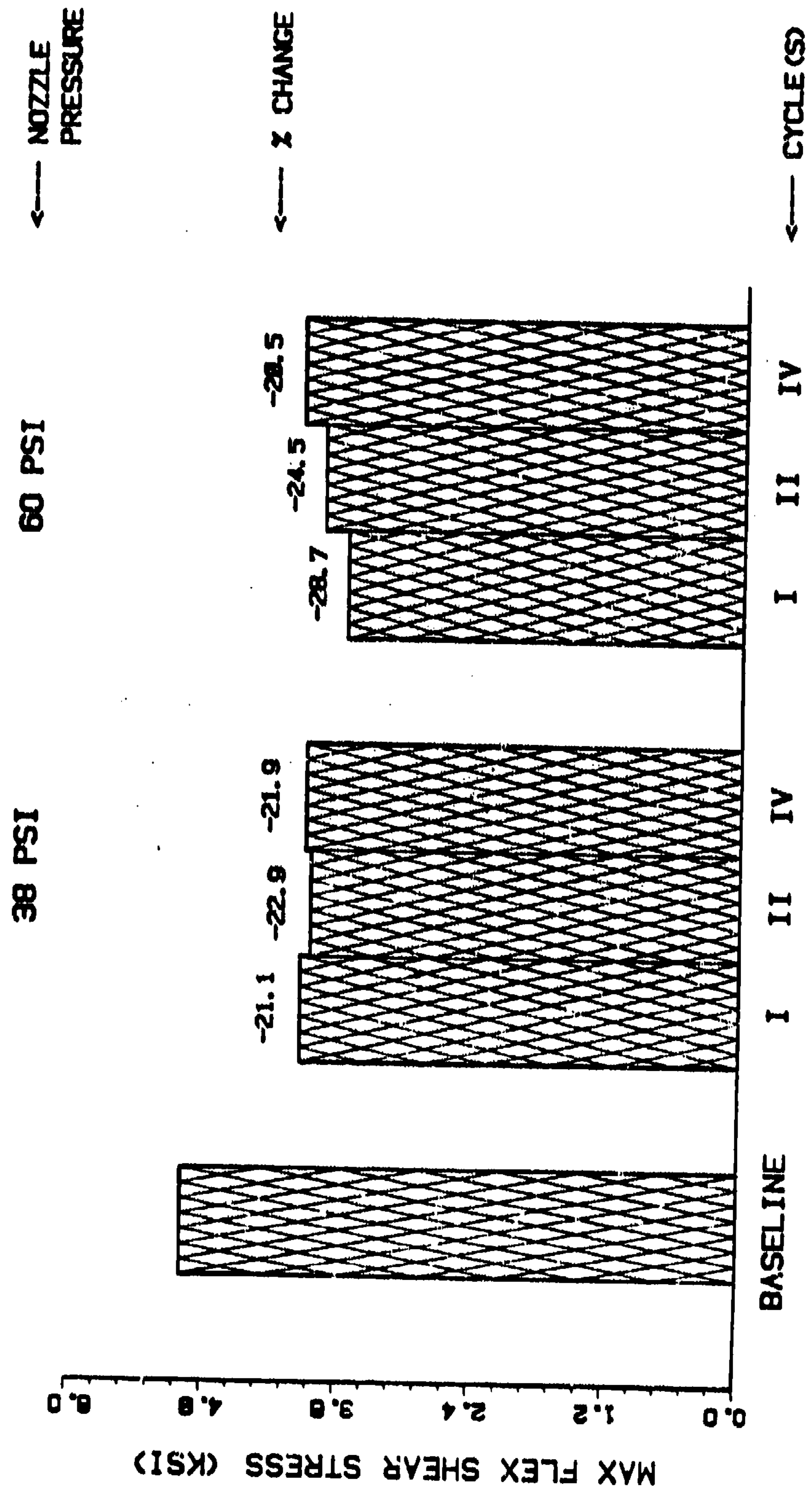


Figure B10. Flexural Shear Strength of AS4/3501-6 with Fiber Orientation $[\pm 45/0/0/90/0]_s$

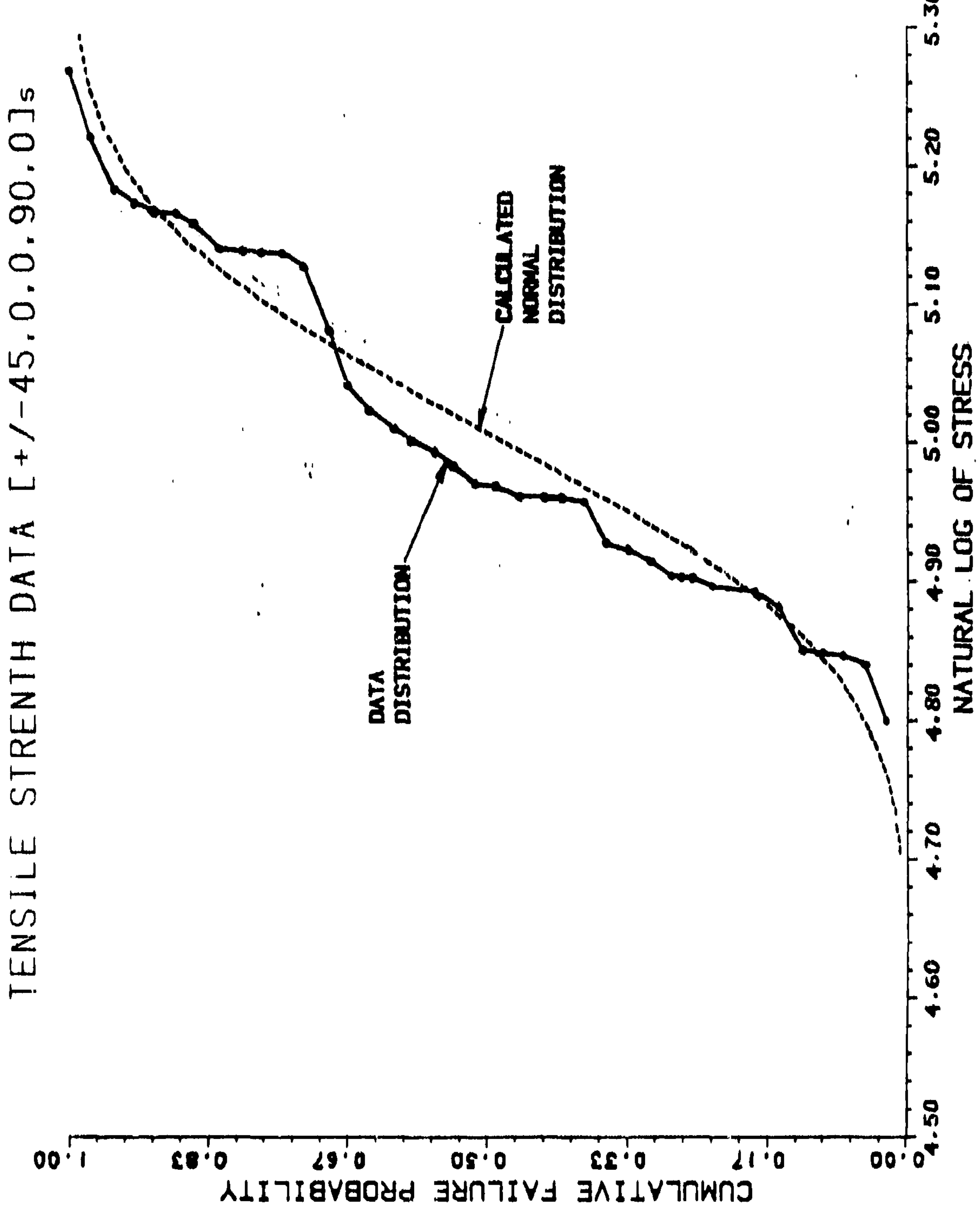


Figure B11. Lognormal Distribution for Tensile Strength of AS4/3501-6 Laminate

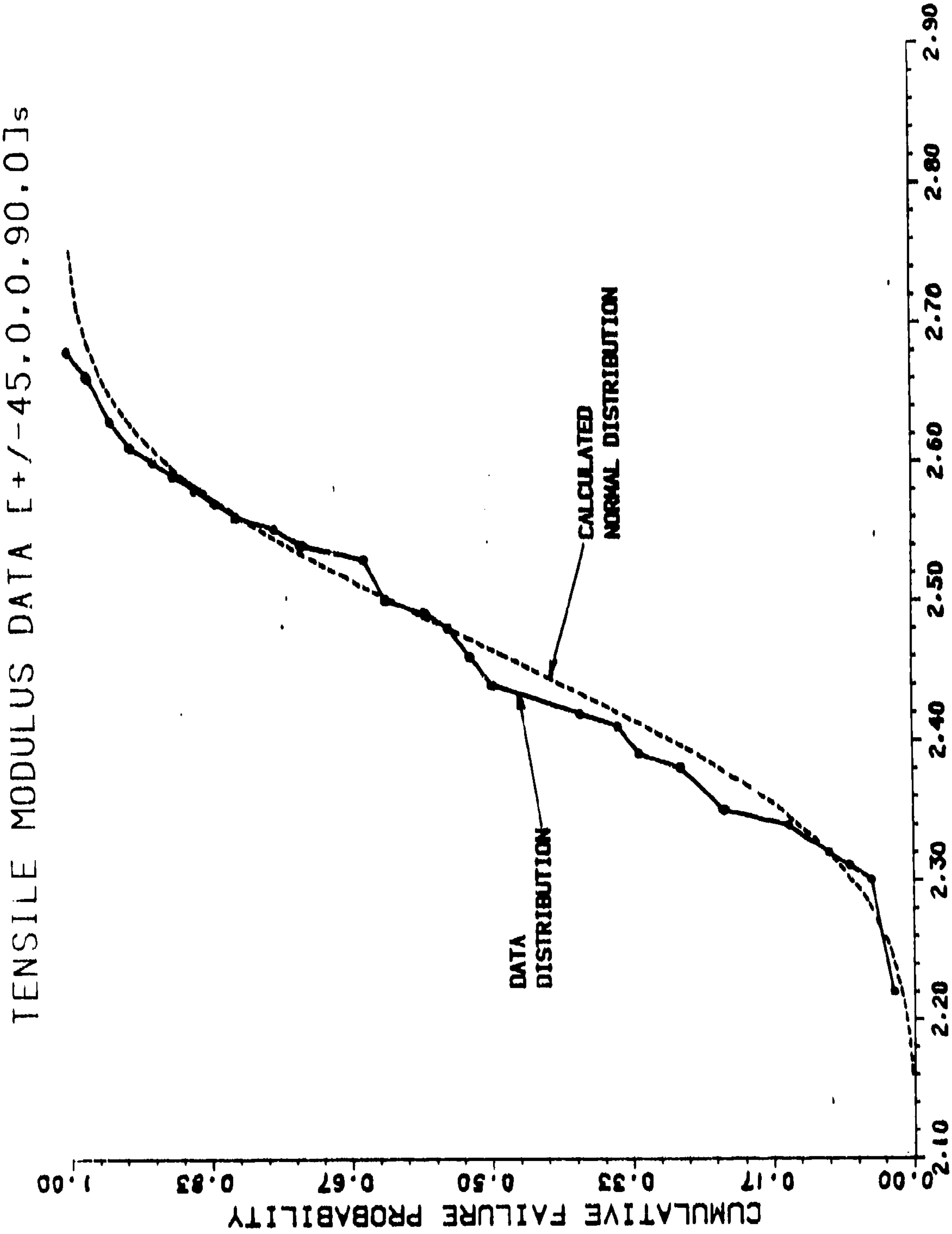


Figure B12. Lognormal Distribution for Tensile Modulus of AS4/3501-6 Laminate

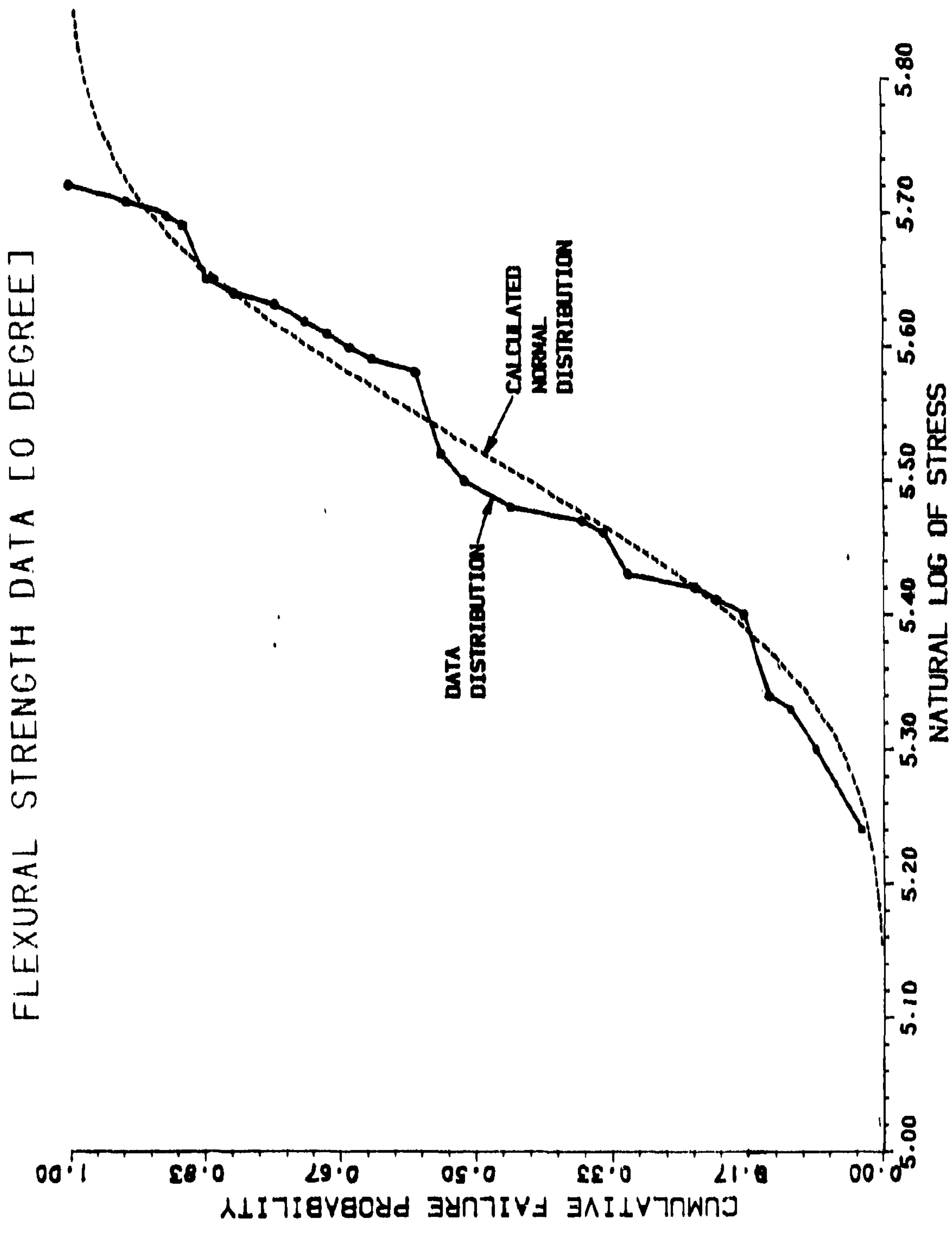


Figure B13. Lognormal Distribution for Unidirectional Flexural Strength of AS4/3501-6

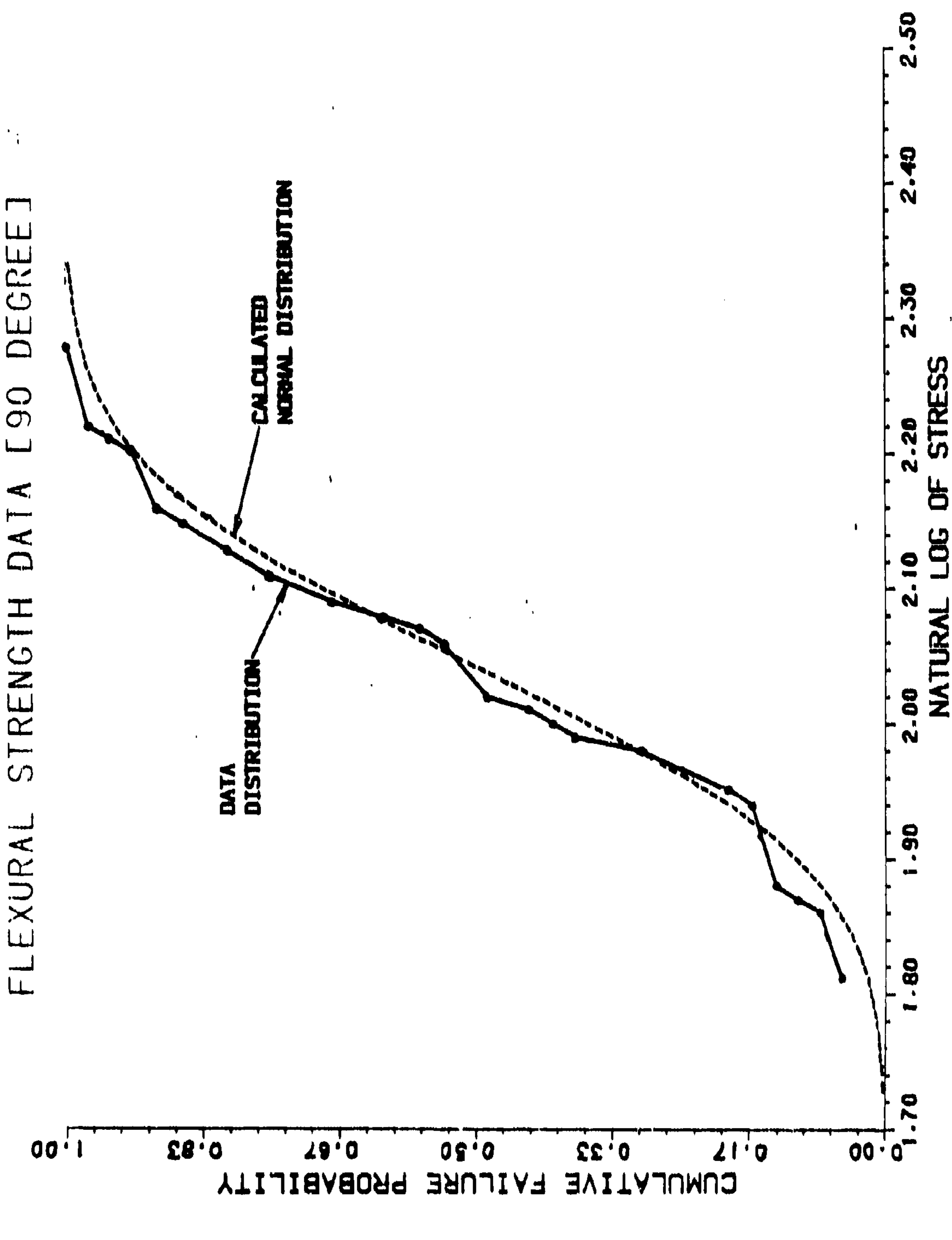


Figure B14. Lognormal Distribution for Unidirectional Flexural Strength of AS4/3501-6 Laminate

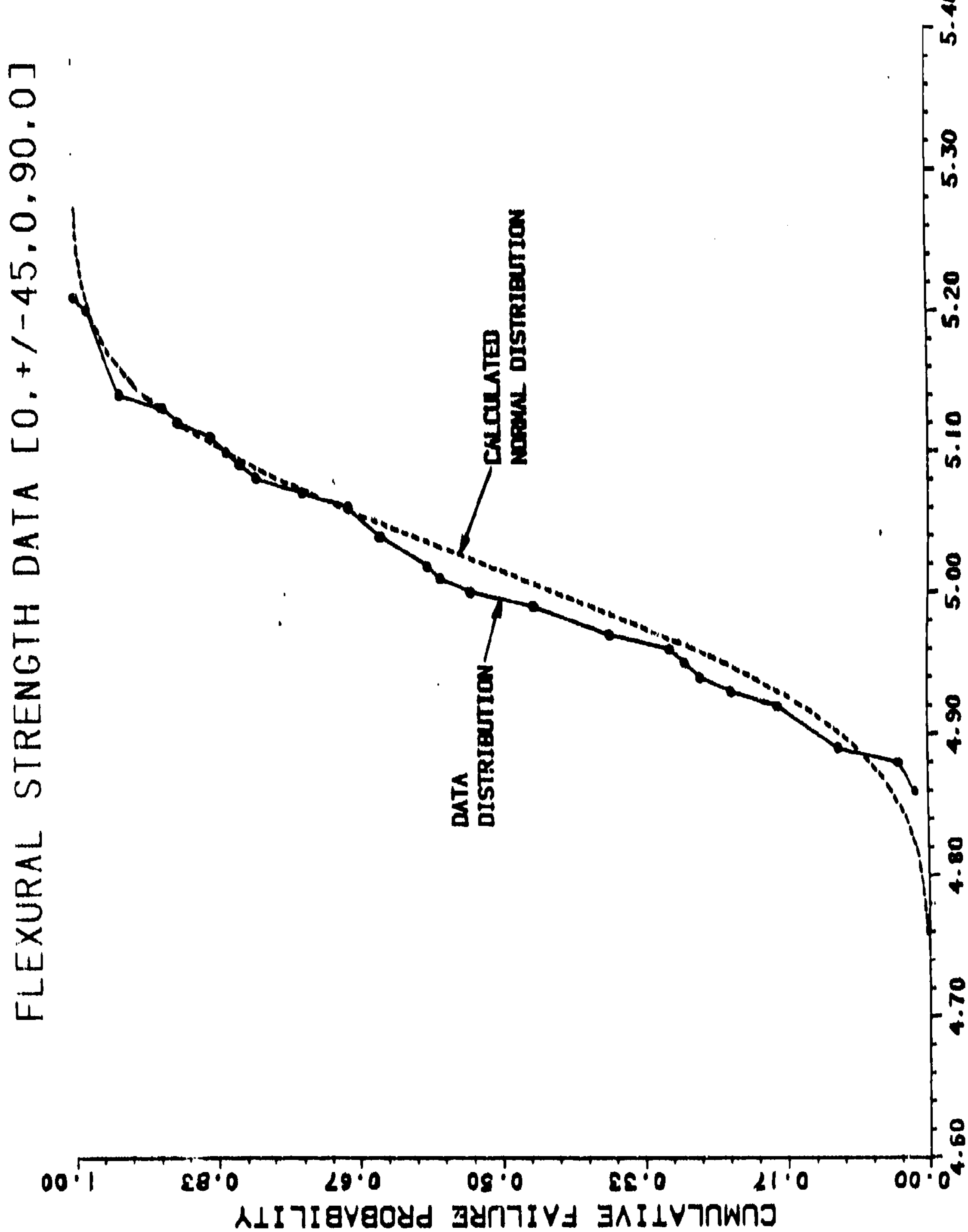


Figure B15. Lognormal Distribution for Flexural Strength of AS4/3501-6 Laminate

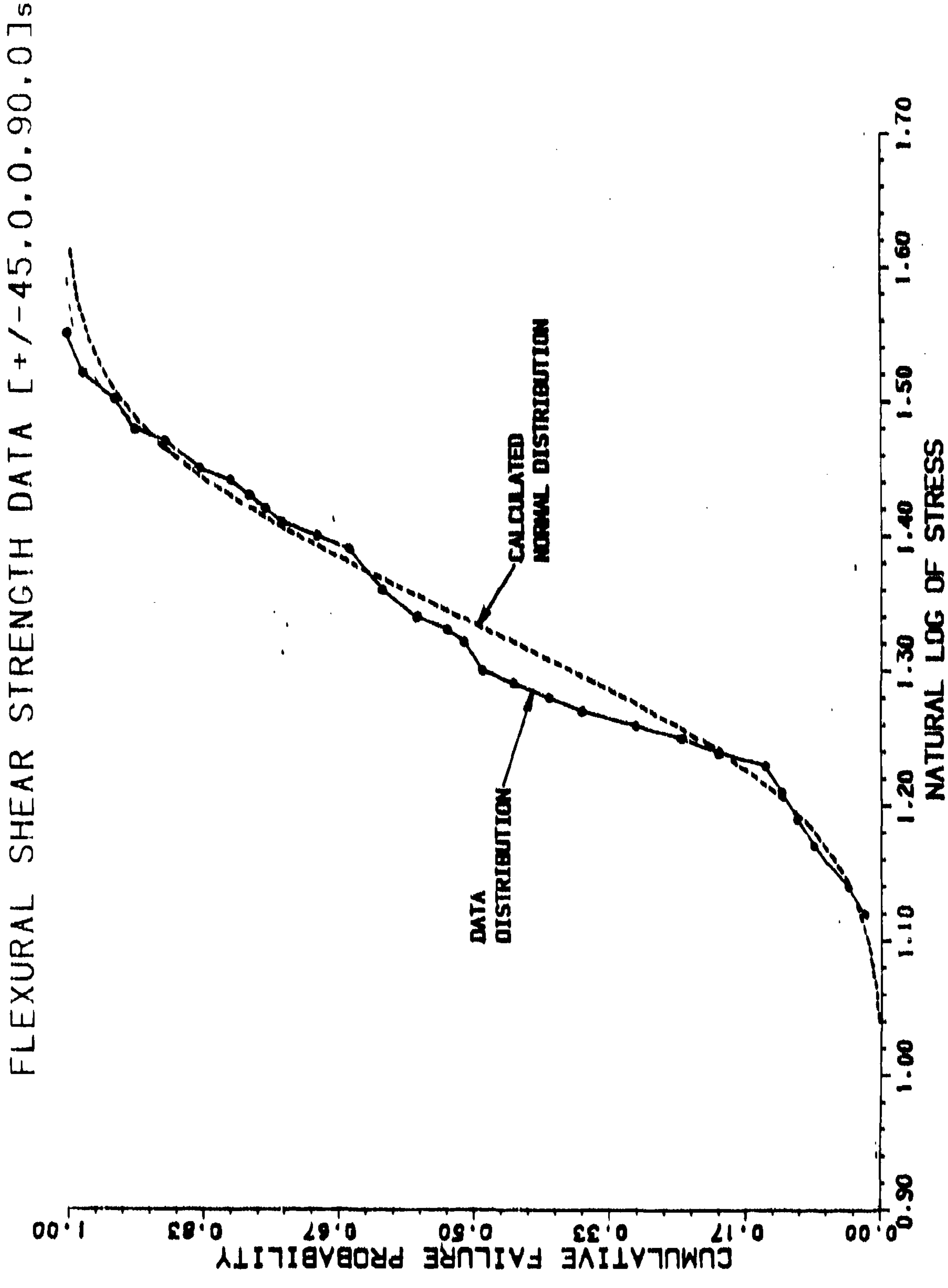


Figure B16. Lognormal Distribution for Flexural Shear Strength of AS4/3501-6 Laminate

TABLE B1

COMPOSITE PANELS (AS4/3501-6)

Panel Nr.	Group Designation	Fiber Orientation	Type of Test	Nr. of Specimens
5	D	$[0/\pm45/0/90/0]_s$	Tensile	40 (1)
9	E	$[90/0/\pm45/0/90]_s$	Tensile	40 (1)
6	F	$[\pm45/0_2/90/0]_s$	Tensile	40 (1)
7	L	$[0/\pm45/0/90/0]_s$	4 Point Flexure	80 (2)
8	M	$[\pm45/0_2/90/0]_s$	4 Point Flexure	80 (2)
14	N	Unidirectional -0° (12 plies)	4 Point Flexure	40 (1)
14	O	Unidirectional -90° (12 plies)	4 Point Flexure	48 (1)

(1) Panel equally divided into 8 groups for: baseline; multi-coat and 1 paint removal (38 PSI); 1 paint removal (38 & 60 PSI); 2 paint removals (38 & 60 PSI) 4 paint removals (38 & 60 PSI).

(2) Panel equally divided into 8 groups for: baseline; 1 paint removal (38 PSI) on tension side and on compression side of specimens; 2 paint removals (38 & 60 PSI); 4 paint removals (38 & 60 PSI).

TABLE B2
TENSILE TEST RESULTS ON AS4/3501-6
FIBER ORIENTATION [0,+/-45,0,90,0]s

Specimen No.	No. of Removals & Nozzle Pressure (PSI)	Ult Stress (KSI)	Initial Modulus (KSI)
D-B1	BASELINE	177.30	13.18
D-B2	BASELINE	132.43	12.57
D-B3	BASELINE	130.89	10.64
D-B4	BASELINE	124.87	10.70
D-B5	BASELINE	173.53	13.66
AVERAGE		147.81	12.15
STANDARD DEVIATION		25.40	1.40
D-IA1	ONE @ 38	166.94	12.25
D-IA2	ONE @ 38	145.67	10.45
D-IA3	ONE @ 38	139.08	10.11
D-IA4	ONE @ 38	126.86	10.87
D-IA5	ONE @ 38	160.60	12.28
AVERAGE		147.83	11.19
STANDARD DEVIATION		16.19	1.01
D-UA1	ONE * @ 38	----	14.41
D-UA2	ONE * @ 38	145.23	14.42
D-UA3	ONE * @ 38	142.70	10.69
D-UA4	ONE * @ 38	144.17	9.72
D-UA5	ONE * @ 38	----	11.76
AVERAGE		144.04	12.20
STANDARD DEVIATION		1.27	2.15

* MULTI-PAINT COATS

D-IIA1	TWO @ 38	158.81	12.13
D-IIA2	TWO @ 38	134.90	11.78
D-IIA3	TWO @ 38	138.99	11.27
D-IIA4	TWO @ 38	129.98	10.80
D-IIA5	TWO @ 38	177.26	12.52
AVERAGE		147.99	11.70
STANDARD DEVIATION		19.69	0.68

TABLE B2 (continued)

Specimen No.	No. of Removals & Nozzle Pressure (PSI)	Ult Stress (KSI)	Initial Modulus (KSI)
D-IVA1	FOUR @ 38	151.08	11.79
D-IVA2	FOUR @ 38	----	10.04
D-IVA3	FOUR @ 38	----	9.57
D-IVA4	FOUR @ 38	141.31	11.49
D-IVA5	FOUR @ 38	----	----
AVERAGE		146.20	10.72
STANDARD DEVIATION			1.08
D-IB1	ONE @ 60	162.03	12.46
D-IB2	ONE @ 60	141.05	11.16
D-IB3	ONE @ 60	136.73	11.88
D-IB4	ONE @ 60	132.43	9.77
D-IB5	ONE @ 60	160.60	12.02
AVERAGE		146.57	11.46
STANDARD DEVIATION		13.81	1.05
D-IIB1	TWO @ 60	----	12.80
D-IIB2	TWO @ 60	138.00	11.49
D-IIB3	TWO @ 60	140.74	9.78
D-IIB4	TWO @ 60	134.87	10.26
D-IIB5	TWO @ 60	164.88	12.33
AVERAGE		144.62	11.33
STANDARD DEVIATION		13.72	1.30
D-IVB1	FOUR @ 60	165.54	----
D-IVB2	FOUR @ 60	127.68	11.34
D-IVB3	FOUR @ 60	104.78	10.31
D-IVB4	FOUR @ 60	146.72	11.16
D-IVB5	FOUR @ 60	179.04	13.24
AVERAGE		144.75	11.51
STANDARD DEVIATION		29.59	1.24

TABLE B3
TENSILE TEST RESULTS ON AS4/3501-6
FIBER ORIENTATION [90,0,+/-45,0,90]s

Specimen No.	No. of Removals & Nozzle Pressure (PSI)	Ult Stress (KSI)	Initial Modulus (KSI)
E-B1	BASELINE	139.90	11.51
E-B2	BASELINE	107.79	9.20
E-B3	BASELINE	102.44	8.39
E-B4	BASELINE	108.09	8.83
E-B5	BASELINE	134.20	9.17
AVERAGE		118.48	9.42
STANDARD DEVIATION		17.22	1.22
E-IA1	ONE @ 38	135.39	10.42
E-IA2	ONE @ 38	113.03	8.39
E-IA3	ONE @ 38	106.25	7.74
E-IA4	ONE @ 38	104.30	8.74
E-IA5	ONE @ 38	128.02	8.22
AVERAGE		117.40	8.70
STANDARD DEVIATION		13.71	1.03
E-UA1	ONE * @ 38	96.22	9.59
E-UA2	ONE * @ 38	118.98	9.59
E-UA3	ONE * @ 38	111.42	7.80
E-UA4	ONE * @ 38	111.34	8.44
E-UA5	ONE * @ 38	131.16	8.93
AVERAGE		113.82	8.87
STANDARD DEVIATION		12.74	0.77

* MULTI-PAINT COATS

Specimen No.	No. of Removals & Nozzle Pressure (PSI)	Ult Stress (KSI)	Initial Modulus (KSI)
E-IIA1	TWO @ 38	133.76	9.33
E-IIA2	TWO @ 38	122.54	8.10
E-IIA3	TWO @ 38	115.22	7.40
E-IIA4	TWO @ 38	107.45	8.19
E-IIA5	TWO @ 38	128.36	8.57
AVERAGE		121.47	8.32
STANDARD DEVIATION		10.43	0.71

TABLE B3 (continued)

Specimen No.	No. of Removals & Nozzle Pressure (PSI)	Ult Stress (KSI)	Initial Modulus (KSI)
E-IVA1	FOUR @ 38	131.31	8.97
E-IVA2	FOUR @ 38	102.29	7.65
E-IVA3	FOUR @ 38	105.93	7.58
E-IVA4	FOUR @ 38	114.59	7.08
E-IVA5	FOUR @ 38	131.53	8.14
AVERAGE		117.13	7.89
STANDARD DEVIATION		13.79	0.71
E-IB1	ONE @ 60	113.87	7.76
E-IB2	ONE @ 60	134.57	9.73
E-IB3	ONE @ 60	112.88	8.63
E-IB4	ONE @ 60	113.46	7.51
E-IB5	ONE @ 60	115.99	9.20
AVERAGE		118.15	8.57
STANDARD DEVIATION		9.25	0.94
E-IIB1	TWO @ 60	132.54	8.41
E-IIB2	TWO @ 60	110.03	8.84
E-IIB3	TWO @ 60	110.89	7.83
E-IIB4	TWO @ 60	122.74	7.78
E-IIB5	TWO @ 60	133.53	8.83
AVERAGE		121.95	8.34
STANDARD DEVIATION		11.31	0.52
E-IVB1	FOUR @ 60	133.50	9.44
E-IVB2	FOUR @ 60	110.93	7.61
E-IVB3	FOUR @ 60	105.95	7.67
E-IVB4	FOUR @ 60	105.65	7.59
E-IVB5	FOUR @ 60	109.73	9.07
AVERAGE		113.15	8.28
STANDARD DEVIATION		11.60	0.91

TABLE B4
TENSILE TEST RESULTS ON AS4/3501-6
FIBER ORIENTATION [+/-45,0,0,90,0]s

Specimen No.	No. of Removals & Nozzle Pressure (PSI)	Ult Stress (KSI)	Initial Modulus (KSI)
F-B1	BASELINE	178.34	12.89
F-B2	BASELINE	131.84	12.08
F-B3	BASELINE	133.62	11.48
F-B4	BASELINE	138.01	11.46
F-B5	BASELINE	175.02	13.33
AVERAGE		151.37	12.25
STANDARD DEVIATION		23.25	0.84
F-IA1	ONE @ 38	184.65	12.92
F-IA2	ONE @ 38	148.50	10.94
F-IA3	ONE @ 38	142.82	10.35
F-IA4	ONE @ 38	142.84	10.07
F-IA5	ONE @ 38	161.82	12.65
AVERAGE		156.12	11.39
STANDARD DEVIATION		17.73	1.32
F-UA1	ONE * @ 38	----	11.70
F-UA2	ONE * @ 38	137.36	10.90
F-UA3	ONE * @ 38	126.66	11.12
F-UA4	ONE * @ 38	144.05	11.51
F-UA5	ONE * @ 38	170.79	12.69
AVERAGE		144.71	11.59
STANDARD DEVIATION		18.80	0.70

* MULTI-PAINT COATS

Specimen No.	No. of Removals & Nozzle Pressure (PSI)	Ult Stress (KSI)	Initial Modulus (KSI)
F-IIA1	TWO @ 38	154.63	13.46
F-IIA2	TWO @ 38	127.48	9.94
F-IIA3	TWO @ 38	127.34	11.47
F-IIA4	TWO @ 38	134.62	10.78
F-IIA5	TWO @ 38	173.34	12.74
AVERAGE		143.48	11.68
STANDARD DEVIATION		20.07	1.43

TABLE B4 (continued)

Specimen No.	No. of Removals & Nozzle Pressure (PSI)	Ult Stress (KSI)	Initial Modulus (KSI)
F-IVA1	FOUR @ 38	176.54	14.60
F-IVA2	FOUR @ 38	145.80	13.91
F-IVA3	FOUR @ 38	147.47	10.34
F-IVA4	FOUR @ 38	142.23	13.11
F-IVA5	FOUR @ 38	175.22	12.86
AVERAGE		157.45	12.97
STANDARD DEVIATION		16.94	1.62
F-IB1	ONE @ 60	170.14	11.23
F-IB2	ONE @ 60	150.16	11.97
F-IB3	ONE @ 60	127.91	9.24
F-IB4	ONE @ 60	134.80	11.28
F-IB5	ONE @ 60	170.44	12.55
AVERAGE		150.69	11.26
STANDARD DEVIATION		19.62	1.25
F-IIB1	TWO @ 60	193.84	13.25
F-IIB2	TWO @ 60	142.71	10.18
F-IIB3	TWO @ 60	133.17	10.47
F-IIB4	TWO @ 60	136.26	10.48
F-IIB5	TWO @ 60	170.45	12.16
AVERAGE		155.28	11.31
STANDARD DEVIATION		26.10	1.34
F-IVB1	FOUR @ 60	151.91	14.37
F-IVB2	FOUR @ 60	143.74	12.13
F-IVB3	FOUR @ 60	121.22	10.77
F-IVB4	FOUR @ 60	133.76	10.49
F-IVB5	FOUR @ 60	168.32	13.65
AVERAGE		143.79	12.28
STANDARD DEVIATION		17.37	1.71

TABLE B5
FLEXURAL TEST RESULTS ON AS4/3501-6
UNIDIRECTIONAL - 0° FIBER ORIENTATION

Specimen No.	# of Removals @ Nozzle Pressure (PSI)	Flexural Strength (KSI)	Apparent Shear Strength (KSI)	Failure Modes (a)
N-B1	BASELINE	300.70	----	T,C
N-B2	BASELINE	229.83	----	T,C
N-B3	BASELINE	304.78	----	T,C
N-B4	BASELINE	240.00	----	T,C
N-B5	BASELINE	236.61	----	T,C
AVERAGE		262.38		
STANDARD DEVIATION		37.05		
N-IA1	ONE @ 38	268.79	----	T,C
N-IA2	ONE @ 38	243.87	----	T,C
N-IA3	ONE @ 38	226.75	----	T,C
N-IA4	ONE @ 38	267.01	----	T,C
N-IA5	ONE @ 38	275.04	----	T,C
AVERAGE		256.29		
STANDARD DEVIATION		20.31		
N-IIA1	TWO @ 38	301.56	----	T,C
N-IIA2	TWO @ 38	248.95	----	T,C
N-IIA3	TWO @ 38	222.02	----	T,C
N-IIA4	TWO @ 38	227.70	----	T,C
N-IIA5	TWO @ 38	285.40	----	T,C
AVERAGE		257.12		
STANDARD DEVIATION		35.14		
N-IVA1	FOUR @ 38	278.32	----	T,C
N-IVA2	FOUR @ 38	240.16	----	T,C
N-IVA3	FOUR @ 38	199.83	----	T,C
N-IVA4	FOUR @ 38	188.43	----	T,C
N-IVA5	FOUR @ 38	266.56	----	T,C
AVERAGE		234.66		
STANDARD DEVIATION		39.70		

TABLE B5 (continued)

Specimen No.	# of Removals @ Nozzle Pressure (PSI)	Flexural Strength (KSI)	Apparent Shear Strength (KSI)	Failure Modes (a)
N-IB1	ONE @ 60	272.58	----	T,C
N-IB2	ONE @ 60	223.65	----	T,C
N-IB3	ONE @ 60	228.32	----	T,C
N-IB4	ONE @ 60	244.60	----	T,C
N-IB5	ONE @ 60	281.25	----	T,C
AVERAGE		250.08		
STANDARD DEVIATION		25.88		
N-IIB1	TWO @ 60	303.47	----	T,C
N-IIB2	TWO @ 60	227.84	----	T,C
N-IIB3	TWO @ 60	208.86	----	T,C
N-IIB4	TWO @ 60	235.33	----	T,C
N-IIB5	TWO @ 60	295.29	----	T,C
AVERAGE		254.16		
STANDARD DEVIATION		42.49		
N-IVB1	FOUR @ 60	270.21	----	T,C
N-IVB2	FOUR @ 60	239.53	----	T,C
N-IVB3	FOUR @ 60	200.74	----	T,C
N-IVB4	FOUR @ 60	206.35	----	T,C
N-IVB5	FOUR @ 60	281.37	----	T,C
AVERAGE		239.64		
STANDARD DEVIATION		36.39		

(a) T - Failure on tensile side of specimen
C - Failure on compression side

TABLE B6
FLEXURAL TEST RESULTS ON AS4/3501-6
UNIDIRECTIONAL - 90° FIBER ORIENTATION

Specimen No.	# of Removals @ Nozzle Pressure (PSI)	Flexural Strength (KSI)	Apparent Shear Strength (KSI)	Failure Modes (a)
O-B1	BASELINE	8.25	----	T
O-B3	BASELINE	8.64	----	T
O-B4	BASELINE	8.60	----	T
O-B6	BASELINE	8.02	----	T
AVERAGE		8.38		
STANDARD DEVIATION		0.30		
O-IA1	ONE @ 38	9.77	----	T
O-IA2	ONE @ 38	9.06	----	T
O-IA3	ONE @ 38	8.08	----	T
O-IA4	ONE @ 38	7.49	----	T
O-IA5	ONE @ 38	7.32	----	T
AVERAGE		8.34		
STANDARD DEVIATION		1.05		
O-IIA1	TWO @ 38	7.21	----	T
O-IIA2	TWO @ 38	6.11	----	T
O-IIA3	TWO @ 38	7.90	----	T
O-IIA4	TWO @ 38	7.56	----	T
O-IIA5	TWO @ 38	6.11	----	T
O-IIA6	TWO @ 38	7.31	----	T
AVERAGE		7.03		
STANDARD DEVIATION		0.76		
O-IVA1	FOUR @ 38	8.61	----	T
O-IVA2	FOUR @ 38	7.32	----	T
O-IVA3	FOUR @ 38	6.97	----	T
O-IVA5	FOUR @ 38	8.06	----	T
O-IVA6	FOUR @ 38	8.24	----	T
AVERAGE		7.84		
STANDARD DEVIATION		0.68		

TABLE B6 (continued)

Specimen No.	# of Removals @ Nozzle Pressure (PSI)	Flexural Strength (KSI)	Apparent Shear Strength (KSI)	Failure Modes (a)
O-IB1	ONE @ 60	8.25	----	T
O-IB2	ONE @ 60	9.11	----	T
O-IB3	ONE @ 60	8.44	----	T
O-IB5	ONE @ 60	9.23	----	T
O-IB6	ONE @ 60	7.85	----	T
AVERAGE		8.58		
STANDARD DEVIATION		0.58		
O-IIB1	TWO @ 60	8.05	----	T
O-IIB2	TWO @ 60	7.06	----	T
O-IIB3	TWO @ 60	7.22	----	T
O-IIB4	TWO @ 60	7.22	----	T
O-IIB5	TWO @ 60	8.45	----	T
O-IIB6	TWO @ 60	6.41	----	T
AVERAGE		7.40		
STANDARD DEVIATION		0.73		
O-IVB1	FOUR @ 60	7.43	----	T
O-IVB2	FOUR @ 60	7.21	----	T
O-IVB3	FOUR @ 60	6.49	----	T
O-IVB4	FOUR @ 60	6.58	----	T
O-IVB5	FOUR @ 60	7.89	----	T
O-IVB6	FOUR @ 60	7.54	----	T
AVERAGE		7.19		
STANDARD DEVIATION		0.55		

(a) T - Failure on tensile side of specimen

TABLE B7
FLEXURAL TEST RESULTS ON AS4/3501-6
FIBER ORIENTATION [0,+/-45,0,90,0]s

Specimen No.	# of Removals @ Nozzle Pressure (PSI)	Flexural Strength (KSI)	Apparent Shear Strength (KSI)	Failure Modes (a)
L-B1	BASELINE	----	5.88	S,C
L-B2	BASELINE	151.19	----	T
L-B3	BASELINE	157.88	----	T,C
L-B4	BASELINE	157.14	----	T,C
L-B5	BASELINE	----	5.73	S,C
L-B6	BASELINE	----	----	C,T
L-B7	BASELINE	167.38	----	T,C
L-B8	BASELINE	162.18	----	T,C
L-B9	BASELINE	165.48	----	T,C
L-B10	BASELINE	171.20	----	T,C
AVERAGE		161.78	5.81	
STANDARD DEVIATION		6.87		
L-IA-C1 (b)	ONE @ 38	191.21	----	T
L-IA-C2	ONE @ 38	----	----	C
L-IA-C3	ONE @ 38	142.39	----	T
L-IA-C4	ONE @ 38	139.24	----	T
L-IA-C5	ONE @ 38	165.58	----	T
L-IA-C6	ONE @ 38	----	5.06	S
L-IA-C7	ONE @ 38	153.99	----	T
L-IA-C8	ONE @ 38	149.57	----	T
L-IA-C9	ONE @ 38	144.12	----	T
L-IA-C10	ONE @ 38	171.10	----	T
AVERAGE		157.15	5.06	
STANDARD DEVIATION		17.74		
L-IA-T1	ONE @ 38	----	4.96	S
L-IA-T2	ONE @ 38	137.44	----	T
L-IA-T3	ONE @ 38	142.41	----	T
L-IA-T4	ONE @ 38	148.77	----	T
L-IA-T5	ONE @ 38	171.44	----	T
L-IA-T6	ONE @ 38	----	4.31	S
L-IA-T7	ONE @ 38	133.55	----	T
L-IA-T8	ONE @ 38	146.41	----	T
L-IA-T9	ONE @ 38	----	5.16	S,C,T
L-IA-T10	ONE @ 38	----	5.44	S
AVERAGE		146.67	4.97	
STANDARD DEVIATION		13.37	0.48	

TABLE B7 (continued)

Specimen No.	# of Removals @ Nozzle Pressure (PSI)	Flexural Strength (KSI)	Apparent Shear Strength (KSI)	Failure Modes (a)
L-IIA1	TWO @ 38	----	4.69	S,C,T
L-IIA2	TWO @ 38	137.20	----	T,C
L-IIA3	TWO @ 38	146.74	----	T,C
L-IIA4	TWO @ 38	155.00	----	T,C
L-IIA5	TWO @ 38	159.57	----	T,C
L-IIA6	TWO @ 38	163.80	----	T,C
L-IIA7	TWO @ 38	133.51	----	T,C
L-IIA8	TWO @ 38	138.45	----	T,C
L-IIA9	TWO @ 38	144.38	----	T,C
L-IIA10	TWO @ 38	167.76	----	T,C
AVERAGE		149.60	4.69	
STANDARD DEVIATION		12.41		
L-IVA1	FOUR @ 38	183.52	----	T,C
L-IVA2	FOUR @ 38	148.00	----	T,C
L-IVA3	FOUR @ 38	144.23	----	T,C
L-IVA4	FOUR @ 38	159.03	----	T,C
L-IVA5	FOUR @ 38	169.90	----	T,C
L-IVA6	FOUR @ 38	181.57	----	T
L-IVA7	FOUR @ 38	150.52	----	T
L-IVA8	FOUR @ 38	140.50	----	T,C
L-IVA9	FOUR @ 38	146.79	----	T,C
L-IVA10	FOUR @ 38	160.87	----	T,C
AVERAGE		158.49		
STANDARD DEVIATION		15.39		
L-IB1	ONE @ 60	----	6.00	S,C
L-IB2	ONE @ 60	147.33	----	T,C
L-IB3	ONE @ 60	141.87	----	T,C
L-IB4	ONE @ 60	138.51	----	T,C
L-IB5	ONE @ 60	----	5.85	S,C,T
L-IB6	ONE @ 60	181.35	----	T,C
L-IB7	ONE @ 60	154.21	----	T,C
L-IB8	ONE @ 60	144.55	----	T,C
L-IB9	ONE @ 60	154.37	----	T,C
L-IB10	ONE @ 60	169.10	----	T,C
AVERAGE		153.91	5.92	
STANDARD DEVIATION		14.62		

TABLE B7 (continued)

Specimen No.	# of Removals @ Nozzle Pressure (PSI)	Flexural Strength (KSI)	Apparent Shear Strength (KSI)	Failure Modes (a)
L-IIB1	TWO @ 60	143.51	----	T,C
L-IIB2	TWO @ 60	137.60	----	T,C
L-IIB3	TWO @ 60	148.39	----	T,C
L-IIB4	TWO @ 60	160.38	----	T,C
L-IIB5	TWO @ 60	138.40	----	T
L-IIB6	TWO @ 60	161.42	----	T,C
L-IIB7	TWO @ 60	133.35	----	T,C
L-IIB8	TWO @ 60	128.52	----	T,C
L-IIB9	TWO @ 60	148.52	----	T,C
L-IIB10	TWO @ 60	----	4.95	S,C
AVERAGE		144.45	4.95	
STANDARD DEVIATION		11.37		
L-IVB1	FOUR @ 60	----	4.76	S,C
L-IVB2	FOUR @ 60	131.98	----	T,C
L-IVB3	FOUR @ 60	139.77	----	T,C
L-IVB4	FOUR @ 60	158.61	----	T,C
L-IVB5	FOUR @ 60	149.86	----	T,C
L-IVB7	FOUR @ 60	147.65	----	T
L-IVB8	FOUR @ 60	133.51	----	T,C
L-IVB9	FOUR @ 60	137.39	----	T
L-IVB10	FOUR @ 60	----	4.98	S,C,T
AVERAGE		142.68	4.87	
STANDARD DEVIATION		9.70		

(a) T - Failure on tensile side of specimen
C - Failure on compression side
S - Shear failure

(b) Compression stress on paint removal side of specimen

TABLE B8
FLEXURAL TEST RESULTS ON AS4/3501-6
FIBER ORIENTATION [±45,0,0,90,0]s

Specimen No.	# of Removals @ Nozzle Pressure (PSI)	Flexural Strength (KSI)	Apparent Shear Strength (KSI)	Failure Modes (a)
M-B1	BASELINE	----	5.05	S
M-B3	BASELINE	----	4.42	S
M-B4	BASELINE	142.54	----	T
M-B5	BASELINE	----	5.50	S
M-B6	BASELINE	----	5.24	S
M-B8	BASELINE	158.30	----	T
M-B9	BASELINE	----	4.35	S
M-B10	BASELINE	----	5.31	S
AVERAGE		150.42	4.98	
STANDARD DEVIATION			0.48	
M-IA-C1 (b)	ONE @ 38	----	4.17	S
M-IA-C2	ONE @ 38	----	3.28	S
M-IA-C3	ONE @ 38	----	3.46	S
M-IA-C5	ONE @ 38	----	4.19	S
M-IA-C6	ONE @ 38	----	3.70	S
M-IA-C8	ONE @ 38	----	3.41	S
M-IA-C9	ONE @ 38	----	3.43	S
M-IA-C10	ONE @ 38	----	3.96	S
AVERAGE			3.70	
STANDARD DEVIATION			0.36	
M-IA-T1	ONE @ 38	----	4.41	S
M-IA-T2	ONE @ 38	103.70	----	T
M-IA-T3	ONE @ 38	113.19	----	T
M-IA-T4	ONE @ 38	----	3.59	S
M-IA-T5	ONE @ 38	----	4.34	S
M-IA-T6	ONE @ 38	----	4.12	S
M-IA-T7	ONE @ 38	115.63	----	T
M-IA-T8	ONE @ 38	----	3.50	S
M-IA-T9	ONE @ 38	----	3.51	S
M-IA-T10	ONE @ 38	----	4.02	S
AVERAGE		110.84	3.93	
STANDARD DEVIATION		6.30	0.39	

TABLE B8 (continued)

Specimen No.	# of Removals @ Nozzle Pressure (PSI)	Flexural Strength (KSI)	Apparent Shear Strength (KSI)	Failure Modes (a)
M-IIA1	TWO @ 38	----	4.49	S
M-IIA2	TWO @ 38	----	3.56	S
M-IIA3	TWO @ 38	----	3.75	S
M-IIA4	TWO @ 38	----	3.80	S
M-IIA5	TWO @ 38	----	4.26	S
M-IIA6	TWO @ 38	----	4.00	S
M-IIA7	TWO @ 38	----	3.48	S
M-IIA8	TWO @ 38	----	3.46	S
M-IIA9	TWO @ 38	----	3.55	S
M-IIA10	TWO @ 38	----	4.10	S
AVERAGE			3.84	
STANDARD DEVIATION			0.36	
M-IVA1	FOUR @ 38	----	4.59	S
M-IVA2	FOUR @ 38	104.07	----	T
M-IVA3	FOUR @ 38	----	3.28	S,T
M-IVA4	FOUR @ 38	----	3.36	S
M-IVA5	FOUR @ 38	----	----	C,T
M-IVA6	FOUR @ 38	----	4.39	S
M-IVA7	FOUR @ 38	----	4.04	S
M-IVA8	FOUR @ 38	----	3.52	S
M-IVA9	FOUR @ 38	118.96	----	T
M-IVA10	FOUR @ 38	----	4.04	S,C
AVERAGE		111.52	3.89	
STANDARD DEVIATION			0.51	
M-IB1	ONE @ 60	----	4.34	S
M-IB2	ONE @ 60	----	3.13	S
M-IB3	ONE @ 60	----	3.05	S
M-IB4	ONE @ 60	----	3.21	S
M-IB5	ONE @ 60	----	3.89	S
M-IB6	ONE @ 60	----	3.89	S
M-IB7	ONE @ 60	----	3.66	S
M-IB8	ONE @ 60	----	3.23	S
AVERAGE			3.55	
STANDARD DEVIATION			0.46	

TABLE B8 (continued)

Specimen No.	# of Removals @ Nozzle Pressure (PSI)	Flexural Strength (KSI)	Apparent Shear Strength (KSI)	Failure Modes (a)
M-IIB1	TWO @ 60	----	4.23	S
M-IIB4	TWO @ 60	----	3.42	S
M-IIB5	TWO @ 60	----	4.16	S
M-IIB6	TWO @ 60	----	3.82	S
M-IIB7	TWO @ 60	----	3.47	S
M-IIB8	TWO @ 60	----	3.53	S
M-IIB9	TWO @ 60	----	3.62	S
M-IIB10	TWO @ 60	----	3.83	S
AVERAGE			3.76	
STANDARD DEVIATION			0.31	
M-IVB1	FOUR @ 60	----	4.59	S,T
M-IVB2	FOUR @ 60	108.05	----	T
M-IVB3	FOUR @ 60	----	3.56	S,T
M-IVB4	FOUR @ 60	----	3.46	S
M-IVB5	FOUR @ 60	----	4.26	S,T
M-IVB6	FOUR @ 60	----	4.13	S
M-IVB7	FOUR @ 60	----	3.64	S
M-IVB8	FOUR @ 60	----	3.65	S
M-IVB9	FOUR @ 60	----	3.61	S
M-IVB10	FOUR @ 60	----	4.72	S
AVERAGE		108.05	3.96	
STANDARD DEVIATION			0.48	

(a) T - Failure on tensile side of specimen
C - Failure on compression side
S - Shear failure

(b) Compression stress on paint removal side of specimen

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